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NASA-CORE

NASA Center of Research Excellence

"Innovative Research for New Technologies"

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Final Progress Report of Fiscal Years 1992-1996

(Grant No. NAGW-2924)

of

The Center for Aerospace Research

NASA Center of Research Excellence (NASA-CORE)

at

North Carolina Agricultural and Technical State University

for

The Performance Period

of

January 1, 1992 to March 31, 1997

Submitted to

National Aeronautics and Space Administration

by

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Chancellor
North Carolina A & T State University

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Interim Director
Center for Aerospace Research

"An Equal Opportunity Employer"
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EXECUTIVE SUMMARY

This is the final report for the NASA Grant No. NAGW-2924. The final report documents the Center's research activities and accomplishments for the performance period January 1992 - March 1997.

In January 1992, NASA established the Center for Aerospace Research: NASA Center of Research Excellence (NASA-CORE) at North Carolina A&T State University (NCA&TSU), as a multidisciplinary research center, and one of seven NASA University Research Centers at Historically Black Colleges and Universities (HBCUs) under the Minority University Research and Education Division. These research centers were established to foster new science and technology concepts, expand the nation's base for aerospace research and development, develop mechanisms for the increased participation by faculty and students at HBCUs in mainstream research, and increase the production of socially- and economically-disadvantaged persons with advanced degrees in NASA-related disciplines. Three engineering departments: Mechanical, Electrical and Industrial Engineering currently participate in the research and student activities of NASA-CORE.

The Center for Aerospace Research has the following objectives: to educate students in aerospace engineering and related technologies, and the conduct of aerospace research to establish a strong aerospace research capability, as well as to enhance opportunities for socially- and economically-disadvantaged persons in the aerospace engineering and technologies profession. In education and training, we have established a quality aerospace education program, through curriculum and laboratory development, to educate and train students in state-of-the-art aerospace research.

In the education and training of students in aerospace engineering at North Carolina A&T State University the Center has played a critical role in the development of the new aerospace engineering programs in all the participating departments. The resources of the Center facilitated the establishment of an Aerospace Engineering Option within the undergraduate mechanical engineering curriculum. The new curriculum with the aerospace engineering option includes eight new aerospace courses, with accompanying laboratory experiments.

The development of the undergraduate curriculum is completed, and the new curriculum with the aerospace option was accredited by ABET, following an accreditation visit in Fall 1995. A copy of the current student handbook with information on all aspects of the undergraduate aerospace option is included as Appendix A. The aerospace option has provided students the opportunity to take traditional aerospace engineering courses that were previously unavailable. It also provides an opportunity for students to develop the necessary background for graduate education and research in NASA-related disciplines.

The creation of an accredited aerospace option is an important accomplishment of the Center and NASA, which seeks to develop and increase the number of graduates in aerospace and other NASA-related disciplines to meet the anticipated need for new engineers through the year 2002. In addition, new aerospace engineering courses and laboratory experiments have also been developed in both the Electrical and Industrial Engineering Departments.

In graduate education, new class and laboratory course sequences have also been developed in all the participating departments. The resources of the Center were cited in the request for the establishment of Ph.D. programs in Mechanical and Electrical Engineering, and the Center continues to support the new doctorate degree programs through research and graduate student support. The first Ph.D. degrees in both Electrical and Mechanical Engineering from North Carolina A&T are expected to be awarded in 1998.

Internships, industrial training and other student outreach activities have been important components of student education and training programs of NASA-CORE. We have strongly encouraged students to participate in summer internship programs in industry and at government laboratories, and in the past five years we have had many summer student interns. The experience enables them to cultivate a strong sense of "professionalism and responsibility" in research and technical work and the dissemination of scientific and technical information. It will also equip them with the skills necessary for research and development in the aerospace industry and government laboratories after their college education. It also creates employment opportunities for the student interns upon graduation.

As an example, in 1995 a master's degree student spent eight weeks during the summer at the U.S. Air Force Academy (USAFA) in Colorado Springs, Colorado, participating in high Mach number (supersonic) flow experiments in the USAFA's Trisonic Wind Tunnel. A thesis resulted from this work. Another more recent example involved two of our graduate students who spent last summer at the Japanese Space Agency laboratories under National Science Foundation fellowships, which they were awarded through a national competition. Similarly, many other students have benefited from internships and other outreach programs of the Center during the grant period. Another master's student used the Dynatup impact facility at Wright Patterson Air Force Base in Dayton, Ohio for the impact testing of sandwich shell composites last year. NASA-CORE will continue to seek such rewarding opportunities for our students in industry and government laboratories.

In other student activities, we hosted the First National Student Conference of the 14 NASA University Research Centers at Minority Institutions, March 31-April 2, 1996. The Conference provided a forum for students participating in research activities to present their research results and findings to their peers, and also gave students the opportunity to learn about the research activities that are being conducted at other research centers. The Conference also created an environment for students to engage in direct technical discussions of research subjects of common interest as well as to encourage, foster and promote student collaboration through joint research activities of mutual interest. The Conference was well attended and drew attendees from NASA, industry, DoD and Universities. It was a very successful conference and the proceedings is included as Appendix B.

In aerospace research, our goal is to build a foundation for a strong research capability in aerospace engineering analyses and design in terms of both human resources and infrastructure. The Center for Aerospace Research conducts interdisciplinary research to advance the state-of-the-art in aerospace research in a strong interdisciplinary framework. In this interdisciplinary research framework, five research components: Aerospace Structures, Controls and Guidance, Computational Fluid Dynamics, Human-Machine Interactions, and Propulsion conduct innovative research to develop robust systems engineering and design tools in support of NASA's mission for the development of enabling high speed aircraft and spacecraft technologies. Researchers at the Center have developed, and are developing techniques, analytical and design tools that will aid in the design of next generation supersonic aircraft, hypersonic vehicles and spacecraft. Some of the research results and accomplishments during the past five years are summarized below.

In structures research, we have developed a new nonlinear finite-element code based on geometrically-exact structural models which account for geometric non-linearities (large rotations and displacements) and three-dimensional stress effects. The outcome of this research is a general total-Lagrangian finite-element code named GESA (Geometrically-Exact Structural Analysis) which has been validated by experimental data and known theoretical solutions. This technology has potential applications in the prediction of large deformations of high speed aircraft and spacecraft structures and will provide aerospace structural engineers a new tool that will aid them to better design aircraft and spacecraft structures. We have also developed the predictive tools to monitor the health of aging aircraft, and built-up and composite-repaired structures using model-referenced Frequency Response Function Optimization and Frequency Response Function Assignment methods, and the model-independent Frequency Response Function Monitoring and Transmittance Function Monitoring techniques. These technologies are very important to the structural technology programs and goals of NASA's Aeronautics and Space Transportation Enterprise. The direct benefit is a safer, economically and technologically competitive high speed aircraft.

A new technology based on fuzzy logic (hybrid fuzzy PID, HFPID) that mimics human response to changing high speed aircraft flying characteristics and a hierarchical controller with PID structure called Hierarchical HFPID (HHFPID) have been developed by the Controls and Guidance group. This technology has applications in the control and suppression of vibration in high speed aircraft, vibrating panels, VSTOL aircraft, etc. We have optimized turbofan engines design using genetic algorithms. To characterize the aircraft engine performance, we evaluated the specific thrust and overall efficiency by optimizing four key parameters: Mach number, compressor pressure ratio, fan pressure ratio, and bypass ratio. After determining the singular influence of each parameter on the objective functions, the two objective functions were combined to examine their interaction in a multi-objective function optimization. Numerical results indicate that genetic algorithms are capable of optimizing complex systems quickly. The resultant parameter values agree well with previous studies.

In aircraft stability and control, we are investigating the performance behavior with varying aerodynamic parameters such as lift coefficient, angle of attack, etc. We have focused on two research topics: Dominant Pole Assignment (DPA) for linear uncertain systems and Linear Quadratic Optimal Bode Plots (LQOBP) which provide another solution to Kalman's inverse problem in terms of gain and phase margins. Ordinarily, it is difficult to analyze the stability and performance characteristics of aircraft with parameter variations. Using DPA and LQOBP, we are addressing the parameter sensitivity on the stability and performance characteristics of the aircraft. The outcome of this research will enable the design of controllers that will greatly enhance the stability and performance of high speed aircraft. This technology will have wide application in both commercial and military aircraft with a potential benefit to the traveling public.

In Human-Machine Systems Engineering, we are conducting research to address human operator (pilot) characteristics that impact handling qualities of supersonic and hypersonic aircraft. Human operator models based on control theories are being developed to define multiattribute experiences of the human pilot and pilot-vehicle integration. An augmented control model of the human operator is being developed to address the effects of interdisciplinary phenomena such as flutter and vibration induced motion on high speed vehicle handling qualities. Another important area of our research focus is the modeling of the interaction of the human operator with complex work systems: discrete and continuous (compensatory and pursuit, and stimulus-response (S-R) compatibility) tasks, the effects of saccadic eye movement in visual information search and induced motion changes during task performance on pilot workload. Our results show that the compensatory gain time of the human operator to be $0.75\pm\ 0.5$ sec; occurring with varying crossover frequencies and phase angles between 63° and 70°, and human operators respond differently to signal pairs and the manners in which S-R signals are presented.

On the effect of saccadic eye movement in visual information search, results show no significant difference in the way subjects identify familiar patterns and a relationship between the types of visual information processing tasks on saccadic eye movement. Also it is found that changes in induced motion affect human workload and degrade performance, while task difficulties affect workload. In addition, a quantitative relationship between workload, task complexity and the system dynamics was derived. These results have wide applications in ongoing NASA research computational models for human factors and human factors/research on human-computer interface (Lyndon Johnson Space Center) and human factors/crew performance research (NASA-Ames). The benefits of the research include a better understanding of the complex work domain and the impact on human-automated system interface, and an assessment tool for human performance in complex systems that include multi-modal interface, group and collaborative (team) dynamics.

In Computational Fluid Dynamics (CFD), we focused our research on the following topics: development of compressible dissipation turbulence model in high speed flows, implementation of boundary layer wall function methodology, experimental and computational investigation of airbreathing propulsion/airframe integration for waverider design and study of fluid/structure interactions and flutter of high speed vehicles. Compressible dissipation models have been developed for use with two-equation turbulence models to investigate the effect of pressure dilatation on the growth of supersonic mixing layers, an important phenomenon in high speed combustors. We have developed a new "eddy viscosity transport" model for turbulent flow prediction to give more accurate surface pressure, skin friction and heat transfer characteristics. The implementation of the wall function in a two-dimensional flow code enabled flow field solutions to be obtained at a speed 30-300 times faster. In hypervelocity flow simulation, we have obtained numerical solutions of scramjet (supersonic ramjet) combustor flow fields. These results have applications in the design of high speed vehicles and scramjet (hypersonic vehicle) propulsion systems. Also, we have completed a numerical study of a control reaction flow which has potential applications in spacecraft thrust vectoring.

In addition, we also conducted interdisciplinary research through the fluid/structure/control analysis of (panel) flutter. This research is being performed with ENSAERO, a NASA Ames multidisciplinary CFD code, obtained from NASA Ames. ENSAERO incorporates the effects of aerodynamic loads (fluid forces) on the structure and the attendant deformations and control, and vice versa. Such interactions have profound effects on the behavior of the panel or aircraft surface. A thorough understanding of the interaction phenomena will enable an accurate prediction of the behavior and design of the structure under adverse conditions to prevent failure. In a paralell effort funded by NASA Lewis, we are investigating the loss mechanisms in duct-strut interactions which characterize Advanced Ducted Propulsors (ADP) to optimize the design of high bypass ratio engines.

Research activities in propulsion were relatively new to our core research program, beginning only in November, 1994. The initial research thrust was in two areas: airframe/engine integration involving multidisciplinary design and optimization (MDO) and engine cycle analysis for High Speed Civil Transport (HSCT) and hypersonic vehicles. In MDO we are continuing to develop methodologies for mathematical operations which include model reduction and approximations, optimization, and sensitivity analyses to analyze the multidisciplinary or highly coupled effects on vehicle performance characteristics. This will enable us to determine effects of aerodymanic parameters, such as Mach number variations, angle of attack, etc. on propulsion system performance: efficiency, specific thrust, etc. An example is fluid/structure/propulsion/control interaction which strongly affects the performance and handling qualities of aircraft. The effort here is to develop methodologies to optimize the aerodynamic characteristics from analytical models. This analysis approach allows the development of high fidelity models using computational modules (Finite Element Analysis, CFD, etc.). The obtained research results and the derived technologies have potential application in HSCT and hypersonic vehicle design.

For our interdisciplinary research program, we have developed a practical model to address cross-disciplinary research methodologies through a functional approach. Within this structure, a unique process of synergistic interaction and the dissemination of information among the different components of the Center to facilitate interdisciplinary research analysis, multidisciplinary optimization and systems integration is established. The expected outcome of this interdisciplinary research framework is the development of a robust systems engineering tool for high speed aircraft and spacecraft design.

As a result of the grant, we have acquired adequate scientific and support equipment to conduct current (and anticipated) research activities. Our equipment infrastructure includes several high-end Silicon Graphics, Inc. (SGI) and Sun Microsystems workstations, including a two-processor SGI Power Onyx and Sun Microsystems SparcStation 20. These workstations are also used as front-ends to off-site supercomputers at NASA Field Centers, other government agencies and supercomputer centers across the country through Internet connectivity for highly computation intensive research problems. The Center also has several personal and Apple Macintosh computers for research and administrative support.

In addition, we have also developed new laboratories: Aerodynamics and Aero Design laboratories, Controls laboratory, Structural Mechanics and Control laboratory, Human-Machine Systems laboratory, and a CFD laboratory (in progress). Within the University structure, the Center is located in the College of

Engineering. On November 1, 1996 NASA-CORE moved into the new Edward B. Fort Interdisciplinary Research Center, where ample space for offices and laboratories has been allocated to the Center. The University continues to make a strong commitment to the Center, and will also continue to provide additional space for offices and laboratories to meet the growing needs of the Center.

During the grant period and especially in the last two years, the Center made measurable progress in its efforts to attract external funding for self-support. To enhance and strengthen our research and educational programs, and to broaden our support base during the grant period, we submitted several proposals, both as prime contractors as well as subcontractors to industry, other institutions, and government agencies, including NASA, especially in 1995 and 1996. As a result, we received several new contracts/grants, including Intergovernmental Personnel Act (IPAs) appointments.

We developed collaborative research with NASA Langley on different projects and also collaborated with and/or received contracts/grants from other NASA Field Centers, such as Lewis, Marshall and Dryden, as well as other institutions and industry. We participated in collaborative research activities with the U.S. Air Force Academy in experimental and computational analysis of high Mach number flow fields over a biconic, and co-wrote proposals with aerospace companies and universities such a Rockwell International and Virginia Polytechnic Institute and State University as subcontractors. We are continuing collaborations with Argonne National Laboratory in CFD and Lockheed Martin, as well as with other government agencies, universities and aerospace companies. These collaborative activities and opportunities have enabled us to develop human resources capital, infrastructure and expertise in NASA-related disciplines and conduct focused research in support of NASA's mission to enhance the Nation's aerospace capabilities and competitiveness.

Another vehicle for collaborative activity is the External Review Board (ERB), which was established in 1996. The ERB includes experienced professionals from the aerospace industry, government agencies such NASA, and academia. As an oversight body, the ERB guides and advises the Center Director on the research goals and activities, as well as other relevant issues of interest to NASA's Strategic Enterprises and NASA-CORE goals.

The ERB is made up of one president, vice presidents, senior managers and technical staff from major aerospace companies, senior civil servants and distinguished university professors. The members bring to bear their broad professional background and expertise in making recommendations to the Center Director about research and technology issues of prime interest to the U.S. Government and the aerospace industry. The ERB advises and makes recommendations to the Director about collaborative research and other opportunities, affiliations and partnerships with industry and other research and academic institutions. This enables the Center to conduct focused research, attract external funded research for self-support, facilitate timely technology transfer of research findings and participate in mainstream aerospace research and development of enabling technologies. In this capacity the ERB plays a complementary role in setting the direction of the Center to meet the technology needs of the present and the future of the U.S. Government and the aerospace industry. The first meeting of the ERB was held October 10, 1996 and the report of the inaugural meeting is attached as Appendix C.

Another vehicle we have used during the five-year grant period is the leveraging of the resources of NASA-CORE to attract external funded research. In dollar amounts, this has attracted over $4 million in research activities to North Carolina A&T in the past five years.

The overall performance or productivity of the Center in terms of research and student education and training during the grant period involves the following measures or outcomes: student enrollment, graduation profile and support levels, publications and presentations and technology transfer. This information is summarized in Fig. 1. This data is also presented in Table 1.

As shown in Fig. 1, 54 students have graduated through the program since 1992, while the total number of students supported by the Center from January 1992 to March 1997 is 102. As such, we have made, and are continuing to make, measurable progress in "filling the pipeline" with graduates who may pursue rewarding careers in aeronautics and space science to meet the diversity and technology needs of NASA and the aerospace industry. In terms of research productivity, NASA-CORE researchers have authored or co-authored 45 refereed journal papers and book chapters, given 121 presentations at national and international conferences and 15 faculty seminars and presentations during the grant period.

During the first four years, the NASA Technical Review Committee (TRC) conducted annual reviews to evaluate the performance of NASA-CORE and determine the progress the Center had made towards its education and research goals and objectives. In general, for the first four years, the TRC's review of the performance of and progress made by NASA-CORE has been favorable. In the education and training of students, our performance has met expectations, particularly at the undergraduate level. An example of this progress is the aerospace option in the undergraduate mechanical engineering curriculum and other curriculum and laboratory development. As stated in the 1994 Annual TRC Report: "The reviewers were very impressed by the development of the curriculum for the aerospace option. Progress is excellent." We have also made significant contributions to graduate student education at NCA&TSU in the areas of Mechanical, Electrical and Industrial Engineering. The results of these commitments are manifested by the student enrollment, graduation and support levels, as shown in Fig. 1 and Table 1.

However, the recent reviews have been somewhat more critical with other aspects of our research activities, mainly our interdisciplinary research. Though our research output and productivity, in terms of individual component research activities, have always been commended, the 1994 TRC's review was critical of the lack of our interdisciplinary research activity and a cohesive focus. In response, we focused on interdisciplinary research in 1995 and developed a functional research model that embraced the five research components, including the integration of students through the Education component. We made measurable progress in our efforts to develop a strong interdisciplinary research tool and we will continue to strive to improve. We also addressed and implemented other recommendations of the TRC.

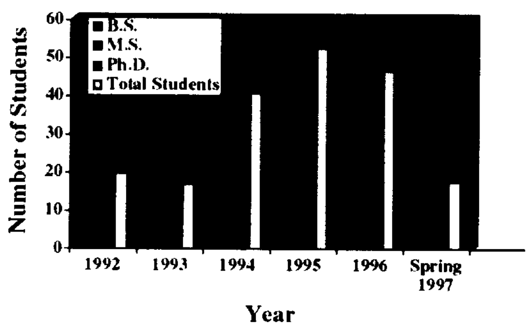
In the following sections are given the publication and presentation lists, and final reports of the education and research components of NASA-CORE in the following sequences: Education Component, Aerospace Structures, Controls and Guidance, Computational Fluid Dynamics, Human-Machine Engineering and

Propulsion. The component reports give more in-depth descriptions of the performance and accomplishments of the research and student activities during the grant period. These performances and accomplishments manifest the program impact of the grant in terms of research and education, including infrastructure, in aerospace engineering at North Carolina A&T State University during the past five years.

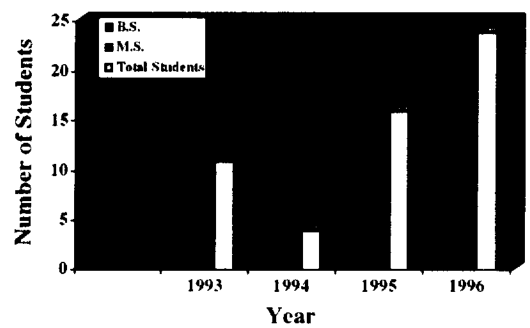
Based on the reported performance and research and educational outcomes, we achieved a significant percentage of our performance goals and expected outcomes in our research activities, student education and training during the grant period. In the area of interdisciplinary research activity we are working diligently to achieve the performance goals and meet every expectation, using the functional model that we have developed to facilitate cross-discipline workflow and MDO.

Program Impact

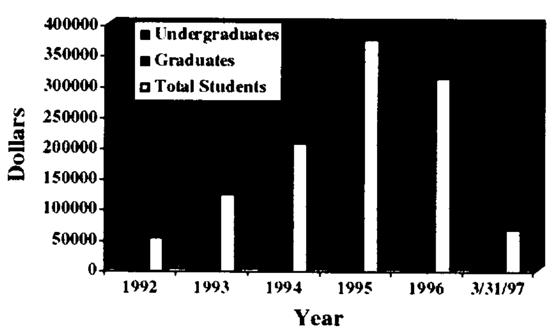
Enrollment Profile



Graduation Profile



Student Support



Refereed journal, book and conference publications, presentations and seminars

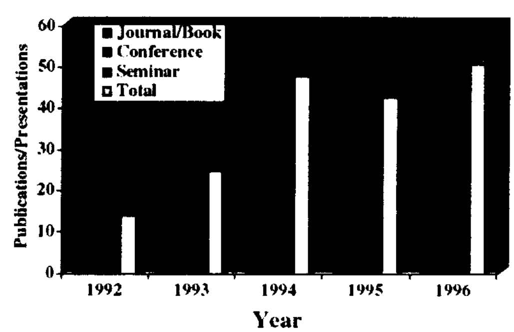


Figure 1. Productivity and Outcomes

Table 1: Productivity and Outcomes

Enrollment Profile

Degrees	Year 1992	1993	1994	1995	1996	Spring 1997
B.S.	14	9	21	24	18	4
M.S.	6	8	20	28	28	13
Ph.D.	0	0	0	1	1	1
Total	20	17	41	53	47	18

Graduation Profile

Degrees	Year 1992	1993	1994	1995	1996
B.S.		2	3	14	16
M.S.		9	1	2	7
Ph.D.		0	0	0	0
Total		11	4	16	23

Student Support

Degrees	Year 1992	1993	1994	1995	1996	3/31/1997
Undergraduates	$ 41,819	26,424	41,480	93,764	46,430	4,619
Graduates	$ 13,645	100,131	167,939	286,806	270,795	64,495
Total	$ 55,464	126,555	209,419	380,570	317,225	69,114

Refereed journal, book and conference publications, presentations and seminars

Publications	Year 1992	1993	1994	1995	1996
Journal/Book	4	7	11	9	14
Conference	10	18	35	24	34
Seminar	0	0	2	10	3
Total	14	25	48	43	51

Table 2: NASA-CORE Student Participation

Component (Coordinator) (Department)	Student			
	Name	Program	Citizenship (Ethnicity/Race)	Graduation (Degree/Date)
Center	Agee, Anissa	Undergraduate	U.S. African-American	BS (ME), May 96
Administration	Baker, Michelle	Undergraduate	U.S. African-American	BS (ME), May 95
	Bowe, Darryl	Graduate (MS)	U.S. African-American	MS(EE), Dec. 97
Daso, Endwell O.	Daniels, Douglas	Undergraduate	U.S. African-American	BS (ME), Dec. 98
(Interim Director)	Dicky, Penda	Undergraduate	U.S. African-American	BS (ME), Dec. 98
	Hoggard, Jerry	Graduate (MS)	U.S. African-American	MS(ME), May 93
	Mebane, Stacey	Undergraduate	U.S. African-American	BS (ME), Dec. 96
	Sawyer, Simone	Undergraduate	U.S. African-American	BS (ME), Dec. 95
Education	Artis, Michael	Graduate (MS)	U.S. African-American	MS(ME), May 93
	Breay, Clifton	Undergraduate	U.S. White-American	BS (ME), May 95
Craft, William	Brooks, Errica	Undergraduate	U.S. African-American	BS (ME), Dec. 97
	Chavis, Christopher	Undergraduate	U.S. African-American	BS (ME), Dec. 97
Mechanical	Graves, Carissa	Undergraduate	U.S. African-American	BS (ME), May 96
Engineering	Hughes, Derke	Graduate (MS)	U.S. African-American	MS(ME), Aug. 97
	Jenkins, Tracey	Undergraduate	U.S. African-American	BS (AE), May 99
	Jeremiah, Wills	Undergraduate	U.S. African-American	BS (ME), Dec. 96
	Johnson, Jenean	Undergraduate	U.S. African-American	BS (ME), May 97
	Kithcart, Mark	Graduate (PhD)	U.S. African-American	PhD(ME), May 98
	Musgrave, Kimberly	Graduate (MS)	U.S. African-American	MS(ME), May 93
	Sharpe, Edwin*	Undergraduate	U.S. African-American	BS (ME), May 97
	Sharpe, Kevin	Undergraduate	U.S. African-American	BS (ME), May 95
	Shine, Tabier*	Undergraduate	U.S. African-American	BS (ME), Dec. 95
	Thorpe, Paul	Undergraduate	U.S. African-American	BS (ME), May 97
	Yarn, William	Undergraduate	U.S. White-American	BS (ME), May 96
Aerospace	Bennett, Adlois L.	Undergraduate	U.S. African-American	BS (ME), May 96
Structures	Cox, James	Graduate (MS)	U.S. African-American	MS(ME), May 93
	Dobbins, Raymond	Graduate (MS)	U.S. African-American	MS(ME), May 93
Pai, P. Frank	Enahora, Basheerah*	Undergraduate	U.S. African-American	BS (ME), May 97
	Fitts, Eddie	Graduate (MS)	U.S. African-American	MS(ME), May 93
Mechanical	Harris, III, Frank	Undergraduate	U.S. African-American	BS (ME), Dec. 95
Engineering	Holshouser, Nicholas	Graduate (MS)	U.S. African-American	MS(ME), GS-INA
	Isom, Elizabeth	Undergraduate	U.S. African-American	BS (AE), Dec. 94
	Lambert, Eric, B.	Undergraduate	U.S. African-American	BS (ME), May 95
	Lambert, Eric, B.	Graduate (MS)	U.S. African-American	MS(ME), GS-INA
	Maynard, Matthew	Graduate (MS)	U.S. White -American	MS(ME), May 97
	Redmond, Jerome	Graduate (MS)	U.S. African-American	MS(ME), May 93
	Rogers, Jacques	Undergraduate	U.S. African-American	BS (EP), May 93
	Turrentine, David	Undergraduate	U.S. African-American	BS (ME), June 97
	Waddell, Dondi	Undergraduate	U.S. African-American	BS (ME), May 97
	Wheater, Eric A.	Graduate (MS)	U.S. White-American	MS(ME), June 97
	White, Shiryl T.	Undergraduate	U.S. African-American	BS (ME), June 97
Controls and	Barnhart, Kevin	Graduate (MS)	U.S. African-American	MS(EE), Dec. 94
Guidance	Bowe, Nadeem	Graduate (MS)	U.S. African-American	MS(EE), Dec. 97
	Chance, Lamark	Graduate (MS)	U.S. African-American	MS(EE), Dec. 94
	Clifton, Charles	Undergraduate	U.S. African-American	BS (EE), May 95
Homaifar, Abdollah	Green, James L.	Undergraduate	U.S. African-American	BS (EE), Dec. 95
	Hogans, John	Graduate (MS)	U.S. African-American	MS(EE), May 94
Electrical	Hunter, Margie	Undergraduate	U.S. African-American	BS (EE), May 97
Engineering	Marsh, Roland	Graduate (MS)	U.S. African-American	MS(EE), Dec. 97
	McCormick, Ed V.	Graduate (MS)	U.S. White-American	MS(EE), Dec. 92
	Nagle, James	Graduate (MS)	U.S. White-American	MS(EE), Dec. 97
	Sanderson, LaWanda	Undergraduate	U.S. African-American	BS (ME), May 96
	Sartor, Kenneth J.	Graduate (MS)	U.S. African-American	MS(EE), Dec. 97
	Smith, Monica	Undergraduate	U.S. African-American	BS (ME), Dec. 94

Table 2: NASA-CORE Student Participation (Continued)

Component (Coordinator) (Department)	Student: Name	Program	Citizenship (Ethnicity/Race)	Graduation (Degree/Date)
Controls and	Smith, Nikki	Undergraduate	U.S. African-American	BS (EE), May 95
Guidance	Tillery, Willie	Undergraduate	U.S. African-American	BS (EE), May 98
	Warren, Rufus	Graduate (MS)	U.S. African-American	MS(EE), Dec. 95
	Williams, Christen B.	Undergraduate	U.S. African-American	BS (EE), May 95
	Williams, Rolanda	Undergraduate	U.S. African-American	BS (EE), May 95
(Continued)	Williams, Rolanda	Graduate (MS)	U.S. African-American	MS(EE), May 96
Advanced Fluids	Baker, Ronald	Graduate (MS)	U.S. African-American	MS(ME), Dec. 96
Research -	Bass, Timothy	Undergraduate	U.S. African-American	BS (ME), Dec. 97
Computational	Boney, Dawn	Graduate (MS)	U.S. African-American	MS(ME), May 97
Fluid Dynamics	Cagle, Corey	Undergraduate	U.S. African-American	BS (ME), Dec. 94
(CFD)	Cagle, Corey	Graduate (MS)	U.S. African-American	MS(ME), Dec. 97
	Chandler, Richard	Graduate (MS)	U.S. African-American	MS(ME), Dec.98
	Gray, Michael	Graduate (MS)	U.S. American (born)	MS(ME), May 93
Chandra, Suresh	Hilliard, Nina	Undergraduate	U.S. African-American	BS (ME), Dec.96
	Jefferies, Damon	Graduate (MS)	U.S. African-American	MS(ME), Dec.97
Mechanical	Jones, Raphael	Graduate (MS)	U.S. African-American	MS(ME), May 97
Engineering	Matthewson, Willie	Undergraduate	U.S. African-American	BS (ME), Dec.96
	Sellers, Cheryl	Graduate (MS)	U.S. African-American	MS(ME), May 93
	Wilson, Leslie	Graduate (MS)	U.S. African-American	MS(ME), Dec.98
	Woods, D'Anthony	Graduate (MS)	U.S. African-American	MS(ME), Dec.97
Human-Machine	Alford, John	Undergraduate	U.S. African-American	BS (IE), May 96
Systems	Bass, Ray	Graduate (MS)	U.S. African-American	MS(IE), INACT
	Bell, Tracey	Graduate (MS)	U.S. African-American	MS(IE), Dec.97
	Brinson, Jermain	Graduate (MS)	U.S. African-American	MS(IE), INACT
Ntuen, Celestine	Burns, Nicole	Graduate (MS)	U.S. African-American	MS(IE), May 96
	Champman, DeShawn	Graduate (MS)	U.S. African-American	MS(IE), May 96
Industrial	Davis, Dorian	Undergraduate	U.S. African-American	BS (IE), May 96
Engineering	Geiger, Christopher	Undergraduate	U.S. African-American	BS (IE), May 93
	Howard, Robert	Graduate (MS)	U.S. African-American	MS(IE), Aug.97
	Jordon, Freda	Graduate (MS)	U.S. African-American	MS(IE), INACT
	Mansfield, Erika	Undergraduate	U.S. African-American	BS (IE), May 95
	Mosley, Carla	Undergraduate	U.S. African-American	BS (IE), May 96
	Pitman, Michelle	Graduate (MS)	U.S. White-American	MS(IE), Aug.96
	President, Lori	Undergraduate	U.S. African-American	BS (IE), May 96
	Ramsey, Sharon	Graduate (MS)	U.S. African-American	MS(IE), May 97
	Reynolds, Kanton	Graduate (MS)	U.S. African-American	MS(IE), Dec. 97
	Roberts, William	Graduate (MS)	U.S. African-American	MS(IE), Dec. 97
	Setzer, Nicole	Undergraduate	U.S. African-American	BS (IE), May 97
	Smith, Andrea	Undergraduate	U.S. African-American	BS (IE), Dec.96
	Smith, Deirdre	Graduate (MS)	U.S. African-American	MS(IE), May 95
	Strickland, Dara	Graduate (MS)	U.S. African-American	MS(IE), Aug.97
	Taylor, Phillip	Graduate (MS)	U.S. African-American	MS(IE), INACT
	Vines, David	Undergraduate	U.S. African-American	BS (IE), May 98
	Watson, Alexandria	Graduate (MS)	U.S. African-American	MS(IE), May 96
	Winchester, Woodrow	Undergraduate	U.S. African-American	BS (IE), May 94
Propulsion	Dunston, Wanita	Undergraduate	U.S. African-American	BS (ME), Dec. 96
	Dunston, Wanita	Graduate (MS)	U.S. African-American	MS(ME), Dec. 98
	Groce, Pamela	Undergraduate	U.S. African-American	BS (ME), May 96
Human, Meldon	King, Leslie	Graduate (MS)	U.S. African-American	MS(ME), May 96
	McCrae, Natasha	Graduate (MS)	U.S. African-American	MS(ME), Dec. 97
Mechanical Engineering	Stephens, Joel	Undergraduate	U.S. White-American	BS (ME), Dec. 95

Note: * ⇒ support from faculty release time, GS-INA⇒ in good standing, academically inactive, INACT ⇒ academically inactive.
ME ⇒ Mechanical Engineering, IE ⇒ Industrial Engineering, AE ⇒ Architectural Engineering, EP ⇒ Engineering Physics

PUBLICATIONS AND PRESENTATIONS

Education Component

1. Kithcart, M. and Klett, D. "Reynolds Analogy Comparison of Dimpled Versus Protrusion Roughness," Heat Transfer in Turbulent Flows, ASME Publication HTD-Vol. 318, Nov. 1995.
2. Kithcart, M. and Klett, D. "Heat Transfer and Skin Friction Comparison of Dimpled Versus Protrusion Roughness," Journal of Enhanced Heat Transfer, Vol. 3, No. 4, pp. 273-280, 1996.
3. Kithcart, M. "Heat Transfer and Skin Friction Comparison of Dimpled Versus Protrusion Roughness," Proceedings of the First First National Student Conference of the National Alliance of NASA University Research Centers at Minority Institutions, Greensboro, NC, March-April 1996, Editors: E.O. Daso and S. Mebane.
4. Craft, W.J., Klett, D.E., Lebby, G., Park E. and Kelly, J.,"Development of an Educational Curriculum in Support of the NASA Center of Research Excellence at North Carolina A&T State University," Proceedings of the First Industry/Academy Symposium on Research for Future Supersonic and Hypersonic Vehicles, North Carolina A&T State University, December, 1994.
5. Hughes, D.R., Craft, W.J. and Kelkar, A.D., "Impact Resistance of the Sandwich Shells used in Aerospace Applications," Proceedings of the First National Student Conference of the National Alliance of NASA University Research Centers at Minority Institutions, Greensboro, NC, March-April 1996, Editors: E.O. Daso and S. Mebane.
6. Walton, M.D. and Craft, W.J., "Fabrication, Testing, and Optimization of Sandwich Composites," Proceedings of the First National Student Conference of the National Alliance of NASA University Research Centers at Minority Institutions, Greensboro, NC, March-April 1996, Editors: E.O. Daso and S. Mebane.
7. Craft, W.J., Hughes, D.R. and Kelkar, A.D., "Low Velocity Impact Damage of Organic Form Core Sandwich Composites," International Conference in Composite Materials, ICCM-11, July 12-16,1997 (accepted).

Aerospace Structures Group

Journal Papers:

1. Pai, P.F., Palazotto, A.N. and Greer Jr., J.M., "Appropriate Stress and Strain Measures for Elastoplastic and Geometrically Nonlinear Analyses," Computers & Structures, submitted.
2. Pai, P.F. and Palazotto, A.N., "Large-Deformation Analysis of Flexible Beams," Int. J. Solids and Structures 33, 1335--1353, 1371--1373 (Authors' Closure), 1996.
3. Pai, P.F. and Palazotto, A.N., "Nonlinear Displacement-Based Finite-Element Analyses of Composite Shells --- A New Total Lagrangian Formulation," Int. J. Solids and Structures 32, 3047--3073, 1995.
4. Pai, P.F., "A New Look at Shear Correction Factors and Warping Functions of Anisotropic Laminates," Int. J. Solids and Structures 32, 2295--2313, 1995.
5. Pai, P.F. and Palazotto, A. N., "Polar Decomposition Theory in Nonlinear Analyses of Solids and Structures," J. Engineering Mechanics 121(4), 568--581, 1995.
6. Pai, P.F. and Nayfeh, A.H., "A New Method for the Modeling of Geometric Nonlinearities in Structures," Computers & Structures 53, 877--895, 1994.
7. Pai, P.F. and Nayfeh, A.H., "A Unified Nonlinear Formulation for Plate and Shell Theories," Nonlinear Dynamics 6, 459--500, 1994.
8. Pai, P.F. and Nayfeh, A.H., "A Fully Nonlinear Theory of Curved and Twisted Composite Rotor Blades Accounting for Warpings and Three-Dimensional Stress Effects," Int. J. Solids and Structures 31, 1309--1340, 1994.
9. Song, X., Schulz, M.J. and Pai, P.F., "An Automated Design Technique for Nonlinear Structures and Controllers," Journal of Vibration and Control (in press).
10. Thyagarajan, S.K., Schulz, M.J., Pai, P.F. and Chung, J., "Detecting Structural Damage Using Frequency Response Functions," J. of Sound and Vibration (accepted).
11. Schulz, M.J., Thyagarajan, K.S. and Slater, J.C., "Inverse Dynamic Design Technique for Model Correction and Design Optimization," AIAA Journal 33, 1486--1492, 1995.
12. Schulz, M.J. and Inman, D.J., "Vibration Suppression by Eigenstructure Optimization," Journal of Sound and Vibration 182, 259--282, 1995.
13. Schulz, M.J. and Inman, D.J., "Model Updating Using Constrained Eigenstructure Assignment," Journal of Sound and Vibration 178, 113--130, 1994.
14. Schulz, M.J. and Inman, D.J., "Eigenstructure Assignment and Controller Optimization For Mechanical Systems," IEEE Journal on Control Systems Technology 2, 88--100, 1994.
15. Shen, J.Y., Sharpe Jr., L. and Keckler, C.R., "Inclusion of Flexibility of a Large Flexible Manipulator System in the Implementation of Its End-Effector Vibration Suppression," International Journal of Modelling & Simulation, Vol.16, No.4, 1996.
16. Shen, J.Y. and Sharpe Jr., L., "Identification of Dynamic Properties of Plate-like Structures by Using a Continuum Model," Journal of Mechanics Research Communications. Vol.22, No.1, 1995, 67--78.
17. Shen, J.Y. and Sharpe Jr., L., et al., "A Continuous Dynamic Model for Tapered Beam-like Structures," Journal of Aerospace Engineering, American Society of Civil Engineering. Vol.7, No.4, October, 1994, 435--445.
18. Shen, J.Y. and Sharpe Jr., L. "A Strain-Energy Criterion for Recognition of Identified Modes of the Continuous Structural Models," Journal of Mechanics Research Communications, Vol.20(6),1993, 507--518.
19. Shen, J.Y., Huang, J.K. and Taylor Jr., L.W., "Timoshenko Beam Modeling for Parameter Estimation of NASA Mini-Mast Truss," Journal of Vibration and Acoustics, Transactions of the American Society of Mechanical Engineers, Vol.115, 1993, 19--24.
20. Shen, J.Y., Huang, J.K. and Taylor Jr., L.W., "Likelihood Estimation for Distributed Parameter Models of Large Beam-like Structures," Journal of Sound and Vibration, (1992) 155(3), 467--480.

Book Chapters:

1. Pai, P.F., "Mechanics of Highly Flexible Beams," Nonlinear Elasticity of Solids, Statics, and Dynamic Stability of Structures, in the series of Stability, Vibration, and Control of Structures, edited by A. Guran and D.J. Inman, Prentice Hall, Englewood Cliffs, New Jersey (in press).
2. Schulz, M.J. and Inman, D.J., "Techniques in Active Dynamic Structural Control to Optimize Structural Controllers and Structural Parameters," Structural Dynamic Systems Computational Techniques and Optimization, edited by C.T. Leondes, Gordon and Breach, Newark, New Jersey (submitted).

Conference Papers:

1. Song, X., Schulz, M.J. and Pai, P.F., "Design and Control of Nonlinear Structures," Sixth Conference on Nonlinear Vibrations, Stability, and Dynamics of Structures, Blacksburg, Virginia, June 9--13, 1996.
2. Abdelnaser, A.S., Pai, P.F., Naghshineh-Pour, A.H. and Schulz, M.J., "Dynamic Characteristics of Skew Cantilevered Trapezoidal Plates," AIAA Dynamics Specialists Conference, Salt Lake City, UT, April 18--19, 1996.
3. Schulz, M.J., Pai, P.F., Thyagarajan, S.K. and Chung, J., "Structural Damage Diagnosis by Frequency Response Function Optimization," AIAA Dynamics Specialists Conference, Red Lion Hotel, Salt Lake City, UT, April 18--19, 1996.
4. Pai, P.F., Schulz, M.J., Naghshineh-Pour, A.H. and Chung, J., "Modeling and Dynamic Characteristics of Composite-Repaired Aluminum Plates," 37th AIAA/ASME/ASCE/AHS/ASC Structures, Structural Dynamics, and Materials Conference, Salt Lake City, UT, April 15--17, 1996.
5. Schulz, M.J., Pai, P.F. and Abdelnaser, A.S., "Frequency Response Function Assignment Technique for Structural Damage Identification," International Modal Analysis Conference, February 12--15, 1996.
6. Pai, P.F. and Schulz, M.J., "Highly Flexible Structures: Modeling, Analysis, and Application to Large Space Structures," Fifteenth Canadian Congress of Applied Mechanics CANCAM '95, University of Victoria, Victoria, Canada, May 28 -- June 1, 1995.
7. Song, X., Schulz, M.J. and Pai, P.F., "Nonlinear Design Technique for Flexible Structures," Tenth VPI&SU Symposium on Structural Dynamics and Control, Blacksburg, Virginia, May 8--10, 1995.
8. Pai, P.F. and Palazotto, A.N., "Three-Dimensional Postbuckling Analysis of Highly Flexible Beams," 36th AIAA/ASME/ASCE/AHS/ASC Structures, Structural Dynamics, and Materials Conference, New Orleans, Louisiana, April 10--13, 1995.
9. Pai, P.F., "Shear Warpings, Shear Couplings, and Shear Correction Factors of Anisotropic Laminates," First Industry/Academy Symposium on Research for Future Supersonic and Hypersonic Vehicles, Greensboro, North Carolina, December 4--6, 1994.
10. Pai, P.F. and Palazotto, A.N., "Modeling and Analysis of Highly Flexible Beams," First Industry/Academy Symposium on Research for Future Supersonic and Hypersonic Vehicles, Greensboro, North Carolina, December 4--6, 1994.
11. Pai, P.F., "Appropriate Stress and Strain Measures for Nonlinear Structural Analyses," Fifth Conference on Nonlinear Vibrations, Stability, and Dynamics of Structures and Mechanisms, Blacksburg, Virginia, June 12--16, 1994.
12. Song, X., Schulz, M.J. and Pai, P.F., "Design and Control of Nonlinear Structures," Tenth VPI&SU Symposium on Structural Dynamics and Control, June 1996, Virginia Polytechnic Institute, Blacksburg, Va.
13. Schulz, M.J., Pai, P.F. and Abdelnaser, A.S., "Frequency Response Function Assignment Technique For Structural Damage Identification," IMAC-XIV Conference, February 12-15, Dearborn, Michigan.
14. Thyagarajan, S.K., Schulz, M.J. and Slater, J.C., "Inverse Dynamic Design Technique For Flexible Structures," Conference Proceedings Paper, First University/Industry Symposium On

High Speed Civil Transport Vehicles, Dec. 4-6, 1994, North Carolina A&T State University, Greensboro, NC.

15. Shen, J.Y. and Sharpe Jr., L., "A Finite Element Model for the Aeroelasticity Analysis of the Hypersonic Panels, Part III: Flutter Suppression," 33rd Annual Technical Meeting of SES, Arizona State University, Tempe, Arizona, October 20-23, 1996.
16. Shen, J.Y. and Sharpe, Jr., L., "A Finite Element Model for the Aeroelasticity Analysis of the Hypersonic Panels, Part II: Determination of Flutter Boundary," the Space'96 Conference: the 5th International Conference on Engineering, Construction, and Operation in Space, Albuquerque, New Mexico, June 1-6, 1996.
17. Shen, J.Y. and Sharpe, Jr., L., "Estimation of Physical Damping Parameters by Using Maximum Likelihood Estimator," the SECTAM XVIII: the 8th Southeastern Conference on Theoretical and Applied Mechanics, Tuscaloosa, Alabama, April 14-16, 1996.
18. Shen, J.Y., Kelly, Jr., J.C. and Ren, W.X., "A Distributed Parameter Model for Global Structural Dynamic Analysis of Aircraft Structures," Proceedings of the SDVNC'95: International Conference on Structural Dynamics, Vibration, Noise and Control, Hong Kong, Dec. 5-7, 1995.
19. Shen, J.Y., Sharpe, Jr., L., and Keckler, C.R., "PDEMOD - A Computer Program for Distributed Parameter Estimation of Flexible Aerospace Structures, Part I: Theory and Verification," Proceedings of the Joint Applied Mechanics & Material Summer Conference, American Society of Mechanical Engineers, University of California, Los Angeles, June 28-30, 1995.
20. Shen, J.Y. and Sharpe, Jr., L., "Aerospace Structural Dynamic Analysis and Control by Using Distributed Parameter Modeling Technique," Invited Presentation at NASA Langley Research Center, Hampton, VA, Feb. 13, 1995.
21. Shen, J.Y., Sharpe, Jr., L., He, Z.Q. and Keckler, C.R., "A Method of Superposing Rigid-Body Kinematics and Flexible Deflection for End-Effector Vibration Suppression of a Large Flexible Manipulator System," Proceedings of the ACTIVE'95: the International Symposium on Active Control of Sound & Vibration, Newport Beach, California, July 6-8, 1995.
22. Shen, J.Y., Sharpe, Jr., L., and Lu, M.F., "Optimal Controller Design for Beam Vibration Suppression by Using Piezoelectric Actuator," Proceedings of the 10th ASCE Engineering Mechanics Conference, Boulder, Colorado, May 21-24, 1995.
23. Shen, J.Y., Sharpe, Jr., L., and Lu M.F., "Deflection Control of Beam-Like Structures by Using Piezoelectric Sensor and Actuator," Presented at 1995 North American Conference on Smart Structures & Materials, San Diego, CA., February 26 - March 3, 1995.
24. Shen, J.Y. and Sharpe, Jr., L., "Computational Control of Flexible Aerospace Systems," Contract Report to NASA Langley Research Center (NAG-1-1436), December 1994.
25. Shen, J.Y., Sharpe, Jr., L., and Lu, M.F., "Optimal Controller Design for Aircraft Panel Vibration Suppression by Using Piezoelectric Actuator," Proceedings of the 1st Industry/University Symposium on High Speed Civil Transport Vehicle, Greensboro, NC. December 4-6, 1994.
26. Shen, J.Y. and Sharpe, Jr., L., "Distributed Parameter Dynamic Model of Aerospace Antenna Structures," Proceedings of the ICVE'94: the International Conference on Vibration Engineering, Beijing, China, June 15-18, 1994.
27. Shen, J.Y., "Aerospace and Aeronautical Structures: Modeling, Identification and Control," Invited Lecture, sponsored by Aircraft Flight Test & Research Center of China, Xian, Shaanxi, China, June 30, 1994.
28. Shen, J.Y., Sharpe, Jr., L., and He, Z.Q., "Vibration Suppression of a Flexible Manipulating System by Using Transfer Matrix Method," Proceedings of the 94' North American Conference on Smart Structures and Materials, Vol.2194: Mathematics and Control in Smart Structures, the International Society for Optical Engineering, Orlando, Florida, 13-18 Feb. 1994.
29. Shen, J.Y. and McGinley, W.M., "Dynamic Analysis of a High Speed Transport Model by Using Piecewise Continuous Timoshenko Beam Model," Proceedings of SPACE'94 -- the 4th

International Conference on Engineering, Construction, and Operations in Space, Albuguerque, New Mexico, Feb., 1994.
30. Shen, J.Y. and McGinley, W.M., "A Finite Element Model for the Aeroelasticity Analysis of the Hypersonic Panels, Part I: Theory," Proceedings of the IASTED International Conference on Modeling, Simulation and Identification, Wakayama, Japan, Sept. 12-16, 1994.
31. Shen, J.Y. and Sharpe, Jr., L., "Recognition of Identified Modes by Using A Strain-Energy Criterion," Presented at SPACE'94 -- the 4th International Conference on Engineering, Construction, and Operations in Space, Albuguerque, New Mexico, Feb., 1994.
32. Shen, J.Y. and Sharpe, Jr., L., "Identification of Dynamic Properties of Plate-like Structures by Using a Continuum Model," Proceedings (Abstracts) of the 31th Annual Technical Meeting, Society of Engineering Science, Texas A&M University, Oct. 10-12, 1994.
33. Shen, J.Y., Abu-Saba, E.G., et al., "A Distributed Parameter Model for the Dynamic Analysis of Beam-like Structures with Varied Sectional Properties," Proceedings of the First SES-ASME-ASCE Joint Meeting, Volume: Dynamic Response and Progressive Failure of Special Structures, University of Virginia, Charlottesville, VA., June 6-9, 1993.
34. Shen, J.Y., Abu-Saba, E.G., and Taylor, Jr., L.W., "A Piecewise Continuous Timoshenko Beam Model for the Dynamic Analysis of Tapered Beam-like Structures," Proceeding of the 2nd Conference on Recent Advances in Active Control of Sound and Vibration, Virginia Polytechnic Institute & State University, April 28-30, 1993.
35. Abu-Saba, E.G., Shen J.Y. and McGinley W.M., "Lumped Mass Modelling for the Dynamic Analysis of Aircraft Structures," Proceedings (Abstract) of the First SES-ASME-ASCE Joint Meeting, University of Virginia, Charlottesville,VA., June 6-9, 1993.
36. Shen, J.Y., Sharpe, Jr., L., and Zhong Q.H., "Collocated Terminal Control of a Distributed Parameter Beam Model," Proceedings (Abstract) of the First SES-ASME-ASCE Joint Meeting, University of Virginia, Charlottesville, VA. June 6-9, 1993.
37. Taylor, Jr., L.W., Shen, J.Y. and Sharpe, Jr., L., "Distributed Parameter Formulation of LACE Satellite Model by Using Transfer Matrix Method," Proceedings of the 9th VPI&SU Symposium on Dynamic & Control of Large Space Structures, Virginia Polytechnic Institute & State University, May 10-12, 1993.
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39. Shen, J.Y. and Taylor, Jr., L.W., "Application of the Transfer Matrix Method to Estimate the Modal Characteristics of the NASA Mini-Mast Truss," NASA Workshop on Distributed Parameter Modeling and Control of Flexible Aerospace Systems, Williamsburg, VA., June, 1992, NASA CP-3242.

Computational Fluid Dynamics Group

1. Elbert, G.J., "A Multi-Directional Finite Difference Scheme for the Euler Equations," 25th AIAA Fluid Dynamics Conference, Colorado Springs, CO, AIAA Paper 94- , 1994.
2. Edwards, J., "A Diagonal Implicit/Nonlinear Multigrid Algorithm for Computing Hypersonic, Chemically-Reacting, Viscous Flows," 32nd AIAA Aerospace Sciences Meeting, Reno, NV, AIAA Paper 94-0762, 1994.
3. Edwards, J. and Chandra, S., "Eddy Viscosity Transport Turbulence Models for High Speed, Two-Dimensional, Shock-Separated Flowfields," 32nd AIAA Aerospace Sciences Meeting, Reno, NV, AIAA Paper 94-0310, 1994.
4. Visai, M., Jones, K.M.., and Chandra, S., "Pressure Dilatation Effects in Modeling High Speed Mixing Layers," 12th U. S. Congress of Applied Mechanics, Seattle, WA, 1994.
5. Baurle, R.A. and Hassan, H.A., "Combustion-Turbulence Interaction in Scramjets," First Industry/Academy Symposium on Research for Future Supersonic and Hypersonic Vehicles, Vol. 1, TSI Press, Albuquerque, NM, pp. 618-622, 1994.
6. Edwards, J. and Chandra, S., "Eddy Viscosity Transport Turbulence Models for High Speed, Shock-Separated Flowfields," 25th AIAA Fluid Dynamics Conference, Colorado Springs, CO, AIAA Paper 94-2275, 1994.
7. Krishnamurthy, R., "Numerical Investigation of Mixing and Combustion in a Hypervelocity Flow," Presented at the First Industry/Academy Supersonic and Hypersonic Vehicles, Greensboro, NC, December 1994, Editors: A. Homaifar and J.C. Kelly, Jr.
8. Edwards, J., "Development of an Upwind Relaxation Multigrid Method for Computing Three-Dimensional Viscous Internal Flows," 33rd AIAA Aerospace Sciences Meeting, Reno, NV, AIAA Paper 95-0208, 1995.
9. Ferguson, F., Chandra, S., Blankson, I., and Anderson, J., "A Design Method for the Construction of Hypersonic Vehicle Configuration," AIAA Paper 95-6009, Sixth International Aerospace Planes Conference, Chattanooga, TN, 1995.
10. Chandra, S., "Shear Layer Modeling of High Speed Flows," International Union of Geodesy and Geophysics XXI General Assembly, Boulder, CO, 1995.
11. Ferguson, F., Daso, E., and Chandra, S., "An Integro-Differential Scheme for the Unsteady Fluid Dynamic Equations," Sixth International Symposium on CFD, Lake Tahoe, NV, 1995.
12. Jones, K., Visai, M., and Chandra, S., "Incorporation of Compressibility Effects in Modeling High Speed Mixing Layers," Sixth International Symposium on CFD, Lake Tahoe, NV, 1995.
13. Ferguson, F., Chandra, S., and Blankson, I., "A Computer-Aided Design Method for Hypersonic Configurations," 8th International Conference on Computer Applications in Industry and Engineering, Honolulu, HI, 1995.
14. Ferguson, F., Chandra, S., and Blankson, I., "A Computer-Aided Design Method for Hypersonic Transports," International Journal of Computers and their Applications, April 1997.
15. Shivakumar, K.N., Cozart, A.A., Krishnamurthy, R., Spear, G. and Avva, V.S., Aero-thermo-chemical Flow and Structural Stress Analyses of a 3-D Braided Composite Ablative Nozzle, 1995 JANNAF Meeting, December 4-8, 1995, Tampa, FL.
16. Sellers, C. and Chandra, S., "Compressibility Effects in Modeling High Speed Mixing Layers", accepted for publication in the International Journal of Engineering Computations, 1996.
17. Krishnamurthy, R., Woods, D.A., and Chandra, S., "Computational Investigation of Mixing and Combustion in High Speed Flows," CFD 96 Conference, Ottawa, Canada, June 1996.
18. Edwards, J.R. and Chandra, S., "Comparison of Eddy Viscosity-Transport Turbulence Models for Three-Dimensional, Shock-Separated Flowfields," AIAA Journal, Vol. 34, No.4, pp. 756-763, 1996.
19. Krishnamurthy, R., Cagle, C. and Chandra, S., "Numerical Simulation of Wing-body Junction Flows," Third LeRC HBCU Research Conference, Cleveland, OH, April 10-11, 1996.
20. Krishnamurthy, R., Barnwell, R.W., Brown, D.L., Auslender, A.H., and Korte, J., "A Wall Function Technique for Accelerating PNS Computations of Compressible Flows", 27th AIAA Fluid Dynamics Conference, New Orleans, LA, AIAA Paper 96-2058, June 1996.

21. Edwards, J., "Development of an Upwind Relaxation Multigrid Method for Computing Three-Dimensional Viscous Internal Flows," AIAA Journal of Propulsion and Power, Vol. 12, No. 1, pp. 146-154, 1996.
22. Edwards, J., "An Implicit Multigrid Algorithm for Computing Hypersonic, Chemically-Reacting, Viscous Flows," Journal of Computational Physics, Vol. 123, No. 1, pp. 84-95, 1996.
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24. Ferguson, F., Chandra, S., Blankson, I., and Anderson, J., and Kothari, A.P., "A Design Method for the Construction of Hypersonic Vehicle Configurations," AIAA Journal (in review).
25. Krishnamurthy, R., Woods, D.A., and Chandra, S.,"A Numerical Study of Mixing and Combustion in High Speed Flows," 9th International Conference on Computer Applications in Industry and Engineering, Orlando, FL, December 1996.
26. Jones, R., Jones, K.M., Edwards, J., and Chandra, S., "Implementation of Compressibility Corrections to One-Equation Turbulence Model for Wall-Bounded Flows," 9th International Conference on Computer Applications in Industry and Engineering, Orlando, FL, December 1996.
27. Jeffries, D.K., Krishnamurthy, R., and Chandra, S., "A Numerical Simulation of a Normal Sonic Jet into a Hypersonic Cross-Flow," NASA University Research Centers Technical Conference, Albuquerque, NM, February 1997.
28. Karkehabadi, R., Chandra, S., and Krishnamurthy, R., "Steady-State Solution of a Flexible Wing," NASA University Research Centers Technical Conference, Albuquerque, NM, February 1997.
29. Krishnamurthy, R., Rogers, R.C., and Tiwari, S.N., "Numerical Study of Hypervelocity Flows Through a Scramjet Combuster," Journal of Propulsion and Power, Vol. 13, No. 1, pp. 131-141, February 1997.
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Controls and Guidance Group

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4. Homaifar, A., Bikdash, M. and Gopalan, V.J., "Design using Genetic Algorithms of Hierarchical Hybrid Fuzzy-PID Controllers of Two-Link Robotic Arms," Journal of Robotic Systems, in special issue on NeuroFuzzy Intelligent Robotic Systems (in press), 1997.
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COMPONENT FINAL REPORTS

Education Component

AEROSPACE EDUCATIONAL PROGRAM

FINAL REPORT

Prepared for

Center for Aerospace Research
NASA Center of Research Excellence (NASA-CORE)
College Of Engineering
North Carolina A&T State University

by

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NASA-CORE
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March 1997

Background

In 1992, The College of Engineering received major funding to establish the Center for Aerospace Research: NASA Center of Research Excellence (NASA-CORE) as one of seven national centers. While the focus of the research is in aerospace engineering, the production of graduates, particularly those underrepresented in the profession, is also an important component of the Center's work. At that time there was no undergraduate curriculum or degree program in aerospace engineering at North Carolina A&T State University to assist in supplying students to work in the Center. Thus, the creation of an aerospace engineering curriculum became a top priority for the Educational Component of NASA-CORE. With the short-term de-emphasis of aerospace-related contracts, and the potential for continued downsizing of commercial aerospace activities in the near future, a conservative approach was taken to the implementation of an aerospace engineering curriculum which involved the establishment of an aerospace option within the existing mechanical engineering undergraduate degree program.

Aerospace Engineering Option

Since available resources and existing employment prospects in the aerospace industry did not favor the establishment of a stand-alone degree program in aerospace engineering, an aerospace option was designed as part of the existing mechanical engineering program. The option diverges from the standard program only in the final three semesters. Since the degree awarded to the graduates of the aerospace option is still the BSME, the option had to provide sufficient background in aerospace engineering to permit graduates to work in the aerospace industry, while retaining sufficient fundamental mechanical engineering content to sustain accreditation as a mechanical engineering program. The option prepares graduates for a career related to the design of aerospace or mechanical engineering components and systems in private industry or within an agency such as NASA, or for an advanced degree in mechanical or aerospace engineering.

A course structure was developed and approved towards the end of the 1992-1993 academic year and was subsequently modified in 1994 to meet a new requirement of the University of North Carolina System limiting all four-year curricula to no more than 128 credits hours.

The option was structured to satisfy all the criteria required for accreditation by the Engineering Accreditation Commission (EAC) of the Accreditation Board for Engineering and Technology (ABET) the national accrediting commission and board for engineering programs.

The curriculum for the aerospace option contains eight courses that are different from the standard mechanical engineering program. These courses are marked by an asterisk on the curriculum outline that is shown on the following page. Course descriptions for the seven required aerospace courses and the six technical electives from which the aerospace option students may choose are provided in Appendix D.

The mechanical engineering program, including the new aerospace option, underwent an ABET accreditation visit in November 1995 which resulted in reaccreditation of the program for the maximum allowable period of six years. This was a very significant outcome for the aerospace option. The option has been assigned a faculty coordinator, Dr. Kenneth Jones, who serves as academic advisor to the aero-option students and who is responsible for overseeing the scheduling and teaching assignments for the aerospace courses, and the purchasing of equipment to support the option.

Nine students have graduated thus far under the aerospace option, and three more are scheduled to graduate at the end of the Spring semester (May '97). Due to the relatively small number of students enrolled in the option, the senior cap-stone design course for the aerospace option, MEEN 580 - Aerospace Vehicle Design, has been opened to non-option students to permit the undertaking

Aerospace Option Curriculum

Fall			Spring		
	Freshman Year				
	Course	**cr**		**Course**	**cr**
GEEN 100	Introd. to Engineering	2	GEEN 102	Comp. Prog for Engrs	2
GEEN 101	Introd. to Engr Graphics	2	CHEM 101	Gen. Chemistry I	3
ENGL 100	Ideas & Expression I	3	CHEM 111	Gen. Chemistry I Lab	1
MATH 131	Calculus I	4	ENGL 101	Ideas & Expression II	3
HIST Elective[1]		3	MATH 132	Calculus II	4
SOC SCI Elective[2]		3	HIST Elective[1]		3
			HEALTH/PE Elective[3]		1
	Total	17		Total	17
	Sophomore Year				
MEEN 226	Manufacturing Processes	2	MEEN 210	Num. Methods in ME	2
MATH 231	Calculus III	4	MEEN 260	Materials Science	2
PHYS 241	General Physics I	3	MEEN 300	Mech. Engr. Lab. I	2
PHYS 251	General Physics I Lab.	1	MEEN 335	Mechanics I, Statics	3
ECON 300/301	Prin. of Econ (micro/macro)	3	MATH 331	Differential Equations	3
HUMANITIES Elective[4]		3	PHYS 242	General Physics II	3
			PHYS 252	General Physics II Lab.	1
	Total	16		Total	16
	Junior Year				
MEEN 336	Strength of Materials	3	MEEN 400	Mech. Engr. Lab II	1
MEEN 337	Mechanics II, Dynamics	3	MEEN 415	Aerodynamics*	3
MEEN 441	Fund. of Thermodynamics	3	MEEN 440	Mechanism Des. & Anal.	3
ELEN 200	Electric Circuit Anal.	3	MEEN 422	Aero. Veh Structures I*	3
ELEN 206	Circuits Laboratory	1	MEEN 474	Engineering Design	3
MATH 332	Applied Engr. Mathematics	3	ELEN 410	Lin. Systems & Control*	3
HEALTH/PE Elective[3]		1			
	Total	17		Total	16
	Senior Year				
MEEN 560	Modern Engr. Materials	3	MEEN 562	Heat Transfer	3
MEEN 565	Des. of Machine Elements	3	MEEN 572	Mech Engr. Seminar	1
MEEN 576	Propulsion*	3	MEEN 580	Aero. Vehicle Design*	3
MEEN 578	Flight Veh. Performance*	3	MEEN 581	Mechanical Vibrations	3
AEROSPACE Elective[5,*]		3	MEEN 577	Aero. and Propulsion Lab*	1
			HUMANITIES Elective[4]		3
	Total	15		Total	14

(Total Credit Hours: 128)

* Denotes course unique to aerospace option

[1]6 hrs of Hist Elective required. See course list and note Black/Global Studies requirement on page 4.

[2]3 hrs of Soc Sci Elective required. See course list and note Black/Global Studies requirement on page 4.

[3]2 hrs of PHED Elective required. Any two 1-credit PHED courses or PHED 200.

[4]6 hrs of HUMANITIES Elective required.

[5]3 hrs of Tech Elective required from MEEN 651, 652, 653, 654, 655, 656. Others as approved by advisor.

of more ambitious design projects. This course has centered around the SAE Aero Design Competition for the most recent two years. Nine students in Spring '96 and fifteen students during Spring '97 have participated in the design and construction of a remote control "high-lift aircraft" for the SAE competition. At the graduate level there is more flexibility in aerospace related studies, and students in the three departments participating in NASA-CORE (ME, EE and IE) normally pursue their own departmental programs of study.

The faculty participating in the Education Component is given in Appendix E. It includes those formally funded through the component and those who contributed through their teaching activities.

Instructional Laboratory Development

The aerospace option includes one laboratory course that is unique to the option, viz. the Aerodynamics and Propulsion Lab. Several pieces of equipment have been purchased to support this laboratory including a shock tube, a gas turbine engine, and improvements to an existing closed circuit subsonic wind tunnel which have included a variable speed motor control and a sting balance. Dr. Ed Schackleford has spent a considerable amount of time developing a laboratory manual for this course, a copy of which is attached as Appendix F.

NASA-CORE funds have been used to support the development of another laboratory that directly supports the aerospace option, the Design and Simulation Laboratory. This PC-based computer laboratory is used extensively by Dr. P. Frank Pai for the MEEN 580 cap-stone design course to teach aircraft design using the Advanced Aircraft Analysis software package and the AIAA aircraft design package.

Graduate Education and Research Activities Supported under the Education Component

Two African-American graduate students have been supported through the Educational Component. Mark Kithcart, is enrolled in the Ph.D. program with research support from the Center. He is doing experimental and analytical work in the area of rough surface subsonic boundary layer flow. Several items of equipment have been purchased through NASA-CORE to support this research including a two-color LDV, three channels of hot wire anemometry, and an infrared radiometer. Two papers based on preliminary rough surface boundary layer work were published by Mr. Kithcart and his advisor, Dr. Klett, in 1996, and Mr. Kithcart presented a paper at the 1996 NASA University Research Centers First Natonal Student Conference.

An MSME student, Derke Hughes, under the guidance of Dr. William Craft, is working in the area of sandwich shell composites. Mr. Hughes is working in the facilities of the Center for Composite Materials Research where he has fabricated sandwich shells which were then tested for impact damage and post-impact environmental degradation. Mr. Derke Hughes and Michael Walden participated in the 1996 NASA University Research Centers First Natonal Student Conference. They presented two papers on sandwich shells.

A list of the papers published under the educational component is given under Publications and Presentations.

STRUCTURES RESEARCH

FINAL REPORT

Prepared for

Center for Aerospace Research
NASA Center of Research Excellence (NASA-CORE)
College Of Engineering
North Carolina A&T State University

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February 1997

A. AREA SUMMARY

The Structures Group currently consists of two assistant professors, one post-doctoral research associate, and several graduate and undergraduate students. Moreover, this group has a Structural Mechanics and Control (SMC) research laboratory to support computational and experimental work. The Structures Group concentrates on research pointed toward the modeling, analysis, and design of light-weight and reliable aerospace vehicle structures. The research focus areas of the structures group are:

1. Development of new approaches in the modeling, analysis, and design of flexible structures, and applications of composite and smart materials to the design and control of aerospace structures.
2. Development of systematic and efficient methods for damage detection and health monitoring of aerospace structures.
3. Nonlinear analyses of wing and panel flutter accounting for aerothermodynamic heating effects and three-dimensional aerodynamic loads.
4. Experimental verification and data-base establishment of static and dynamic characteristics of highly flexible structures.
5. Development of a structural mechanics and control research laboratory to provide governmental and private clients expertise in the test and evaluation of advanced aerospace structures.
6. Development of an educational structural mechanics laboratory to exhibit static and dynamic behaviors and control of aerospace structures and to provide working space and facilities for students in aero design courses.

B. AREA RESEARCH PROJECTS

B.1 Work Completed

B.1.1. Modeling, Analysis, and Design of Highly Flexible Structures

Aerospace structures are designed to be light-weight and strong in order to increase the vehicle performance and to reduce weight. To accomplish these competing goals, structural engineers are required to design structures to have a finite life after which failure due to fatigue may occur. To reduce structural weight, aero vehicle structures are often designed to work even in a post-buckling state with safety factors as low as 1.25 to 1.5 for manned vehicles and 1.1 to 1.25 for unmanned vehicles. Moreover, the significantly increased use of flexible structures in recent rapid developments in aerospace exploration has stimulated extensive research into the mechanics and design of flexible structures. Since the dimensions of space structures are much larger than the shroud diameter of launch vehicles, they are designed to be deployable or need to be constructed in space by assembling unit structures. Such flexible structures can undergo very large displacements and rotations without exceeding their elastic limits. Hence new advances in geometrically nonlinear modeling and computational methods are needed in the analysis and design of such flexible structures.

Some space structures with simple geometries (e.g., solar collectors, dish antennas and radar arrays) can be designed to be deployable by using elegant mechanisms. Other large space structures are usually indeterminate truss type structures constructed by assembling unit truss structures. Unfortunately, deployable structures may bind during deployment due to the unknown thermal environment and other effects. For assembled structures, assembly tolerances and variation of member length due to fabrication and unknown thermal effects cause mismatch of components during construction and distortion of the assembled structure. For mismatch during the construction, large forces are required by the astronauts or the automated assembly end effector to force compatibility for assembly, which involves extensive Extra Vehicular Activity (EVA) and increases the operation time and cost. For distorted precision structures, extra shape control mechanisms are required, which increases the cost and the difficulty in the structural analysis and control.

Because of these existing difficulties in the development and use of current large space structures, it is necessary to investigate alternative ways of constructing large space structures. We study different ways of designing more mechanism-free deployable large space structures by using highly flexible structures (e.g., cables, beams, plates, and shells). However, to understand the behavior of such flexible structures new advances in modeling methods and computational structures technology are necessary in order to evaluate their actual load carrying capacity, to prevent them from undergoing plastic deformations and thermo-induced deformation and vibrations within mission operations, and to determine efficient control strategies.

Available finite-element codes (such as NASTRAN, ABAQUS, ANSYS, Computational Structural Mechanics (CSM) testbed software system) are inaccurate because of the use of inappropriate stress and strain measures, large rotational degrees of freedom (DOF), updated Lagrangian formulations, and/or truncated nonlinear strain-displacement relations, or inefficient because of the use of corotated elemental reference frames, finite rotational DOFs, quarternions, and/or triads. Moreover, intensive computation is involved in nonlinear finite-element analyses of large practical structural systems because it requires incremental/iterative solution procedures, repeated generation of element matrices, assembly of global matrices, solution of large systems of linear equations, eigen solutions, and design sensitivity and optimization analysis.

A new systematic nonlinear modeling technique using Jaumann stresses and strains and new concepts of local displacements and orthogonal virtual rotations has been developed and used to derive geometrically-exact structural models for cables, membranes, beams, plates, and shells by the researchers of the Structures Group of NASA-CORE. These structural theories use a total-Lagrangian formulation and fully account for geometric nonlinearities (large rotations), large displacements, extensionality, large strains, initial curvatures, three-dimensional stress effects, and anisotropy of materials. These formulations are different from other approaches in the literature and provide straightforward explanation and very clear insight into the physical meanings of all structural and inertial terms. Moreover, energy and Newtonian approaches are fully correlated in these derivations and all structural and inertial terms can be interpreted in terms of vectors.

Based on the derived geometrically-exact structural theories, a general total-Lagrangian finite-element code named GESA (Geometrically Exact Structural Analysis) has been under development. In GESA, only global translational DOFs and their derivatives are used and no independent rotational Degrees Of Freedom (DOFs) are defined. A corotated point reference frame is defined by using the symmetry of Jaumann strains. No relative rotational DOFs are used, and only global displacements are used in the strain-displacement relations. Moreover, there is no need for transformations before updating strains, stresses, and displacements. Available results show that GESA is very accurate and efficient in computation. Results from GESA have been validated by available exact solutions and experimental results. The shell theory and the finite-element formulation developed by our center has been used to perform accurate analyses of the tires of the Space Shuttle by Dr. James M. Greer, Jr. of the Flight Dynamics Directorate, Wright Laboratory.

B.1.2. Analysis and Design of Smart Surface Structures for High-Speed Aircraft

One of the competing design parameters in the development of supersonic and hypersonic aircraft is the gross weight of the vehicle. As the flight Mach number approaches supersonic and hypersonic speeds, such as the High Speed Civil Transport (HSCT) and other NASP derived Mach 4-8 aircraft of interest, it becomes increasingly important to employ light-weight flexible structures to minimize the total weight of the aircraft. However, such flexible structures may undergo large deformations and vibrations due to aerothermodynamic loads at supersonic and hypersonic speeds. Hence, nonlinear structural analysis and design/control of flexible structures subjected to aerothermodynamic loads are necessary in order to validate high speed aircraft at supersonic and hypersonic speeds.

Panel flutter and structural integrity have received renewed interest due to the many high speed aircraft under development. Panel flutter is a self-excited dynamic instability of thin plate or shell-like structural components of flight vehicles in the supersonic/hypersonic regime. When an aircraft travels at speeds much above Mach 1, friction (viscous dissipation) causes considerable heating of the aircraft skin. The attendant rise in surface temperature causes thermal deflections of the aircraft skin. Studies show that this could induce flutter at a low critical dynamic pressure. This could affect structural integrity, reduce the fatigue life of skin panels, and result in aircraft stability and performance penalties.

Panel flutter differs from aeroelastic wing flutter in that the aerodynamic force acts only on one side of the panel. Linear structural theory indicates that there is a critical dynamic pressure above which the panel motion becomes unstable and grows exponentially with time. The linear structural theory predicts the flutter boundary and frequency only. Since the amplitude of panel vibration can be large, the effect of in-plane stretching forces and hence geometric nonlinearities need to be included in the model. The in-plane stretching forces tend to restrain the panel motion so that bounded limit-cycle oscillations are observed. The amplitude of limit-cycle oscillations grows as the dynamic pressure increases. Due to aerodynamic pressure the panel deflection is not symmetric with respect to the mid-span of the panel. The existence of limit-cycle oscillations suggests that a nonlinear structural theory be used. The limit-cycle oscillations often result in a panel fatigue failure.

To manage panel flutter and extend structural fatigue life, the conventional approach is to increase the panel stiffness by using thick panels, which increases the gross weight of the vehicle. Due to the requirements for energy-efficient and minimum-weight vehicles, fiber-reinforced laminated composite panels have been increasingly used in order to reduce weight. Another advantage of using composites is that adaptive materials can be embedded into such composite laminates during manufacturing. With the inclusion of adaptive materials, the concepts of smart structures and active dynamic control can be realized and hence lighter and more flexible panels can be used with an appropriate control algorithm.

Although it is almost impossible to completely suppress thermal buckling by using current available distributed actuators (e.g., piezoelectric materials PZT and PVDF), it is possible to control the buckled shape by using integrated smart materials to reduce or circumvent the influence of undesirable phenomena that may affect the panel's aerodynamic characteristics or result in local areas of intense aerodynamic heating.

Nonlinear analyses of panel flutter has been under study from the very beginning of this center. A 15-DOFs Discrete Kirchhoff Theory (DKT) triangular element has been developed, which has 9 bending DOFs and 6 membrane DOFs. In the developed finite-element model, geometric nonlinearities are included by using von Karman strains, aerodynamic loads are included by using the first-order, second-order, and third-order piston theories, and the aerothermodynamic heating effect is included by imposing an assumed temperature distribution. The corresponding algorithm has been programmed in FORTRAN language. Flutter boundaries, effects of temperature distributions, aerodynamic loads using different piston theories, and structural geometries on the flutter speed have been investigated.

A novel active structural damping technique based on nonlinearly coupling structures with electronic circuits has been developed. We have been supported by the Army Research Office to investigate the use of internal resonance and saturation damping techniques to suppress vibrations of helicopter rotor blades. These techniques can be further extended to control flexible composite panels by using integrated piezoelectric actuators and sensors.

B.1.3. Damage Detection and Health Monitoring of Aircraft Substructures

To extend the service life of aging aircraft, a repair method using laminated composite patches to reinforce cracked aluminum components is promising because composite laminates are non-corroding, conformable, and easy to fabricate and possess high stiffness, high strength, and light weight characteristics. However, the repair patches are subjected to curing pre-stress, static and dynamic loads, and thermal stresses. Experimental results show that the most likely damage to such composite repaired structures is debond between the adhesive layer and the aluminum plate. In order to ensure safe operating conditions, it is necessary to monitor the integrity of repair over long service periods. Moreover, the health of large structures (e.g., aircraft components, reusable launch vehicles, and space structures) can be more appropriately monitored by using vibrometry techniques. The principal considerations in designing a vibration-based health monitoring system are accuracy, sensor type, and the damage detection algorithm.

With the support of NASA-CORE and Raytheon E-Systems Inc., we have developed practical health monitoring techniques for built-up and composite-repaired structures. These include the model-referenced Frequency Response Function Optimization (FRFO) and Frequency Response Function Assignment (FRFA) methods, and the model-independent Frequency Response Function Monitoring (FRFM) and Transmittance Function Monitoring (TFM) techniques. The FRFA method is an analogy to the eigenstructure assignment method, but the frequency response function is assigned rather than eigendata. Non-proportional damping and dynamic expansion are used to improve accuracy of the technique. A reverse procedure is used to design structures and control systems to suppress vibration, and to precisely diagnose structural damage using the vibration signature of the structure. Simulated damage to a bridge truss structure has been successfully identified using a movable sensing approach. The TFM technique is a very unique approach because it can use natural excitation, that is, the excitation does not need to be measured.

Advantages of the TFM method are: (1) no structural model is needed, (2) the excitation does not need to be measured, (3) damage can be detected using random ambient vibration, (4) the non-resonant and anti-resonant (zeros) parts of the TFs are very sensitive and can detect small damage (cracks) that modal methods miss, (5) simultaneous multiple damage can be detected, (6) well developed sensor and signal processing techniques are used rather than unproven impedance methods, (7) the TFM is a highly repeatable diagnostic procedure because environmentally induced changes in the physical properties of the structure are mostly canceled by the ratio of response quantities in the TF, (8) large structures can be monitored during ground vibration testing using a Scanning Laser Doppler Velocimeter, (9) the TFs have a high dynamic range and can decompose the response signal/noise into different frequency bands to focus on abrupt spectral changes due to damage, and (10) the TFM technique is algorithmically simple and suitable for on-line autonomous damage detection.

A report on our health monitoring techniques has been sent to Mr. Chuck Wilkerson who is the head of the NDE group on the Reusable Launch Vehicle (RLV) program at NASA Marshall Space Flight Center. He is interested in applying the health monitoring research to verify the integrity of RLVs after each flight.

B.1.4. Static and Dynamic Experiments on Flexible Structures

Much of the HSCT research program is directed at developing advanced materials. This research on airframe materials and structures includes developing, analyzing, and verifying the technology needed to achieve structural weight reductions of 30--40% for the current Mach 2.4 baseline airplane with a 60,000-hr life (the normal 20-year life span of a commercial aircraft) - including 50,000 hr at temperatures up to 400 F. Researchers need to investigate advanced light-weight structural concepts using aluminum and titanium alloys, polymer matrix composites, and high-temperature adhesives and sealants. Suitability for low-cost manufacture is a critical consideration, and verification testing needs to be done on large-scale components.

A Structural Mechanics and Control (SMC) research laboratory has been developed and equipped for static and dynamic testing of structures. The SMC research laboratory is for the research and development of advanced aerospace and space vehicle structures. The equipment in this laboratory includes two Ling vibration shakers (900, 200 lbf), four 50-lb shakers, two function generators, four digital oscilloscopes (4 channels), an FFT analyzer (16 channels), modal testing equipment (accelerometers, load cells, power generators, power supply/conditioners, calibrator, signal conditioning modules, velocity sensors, large displacement and acceleration sensors) with STARStruct software, two dSPACE controllers, two LabVIEW data acquisition and controllers, two 486 personal computers, four Pentium computers, one SUN SPARCstation-20, NASTRAN, ASTROS version 11, MATLAB, and other supporting hardware and software.

The modal testing equipment in the SMC laboratory has been used to test the dynamic characteristics of beams, swept tapered aluminum plates (simulating aircraft wings), composite shells, and built-up structures. Some of the modal test results have been used to validate and correlate with the results of finite-element analyses using NASTRAN. Moreover, Dr. Tony Anderson of the Mechanical Engineering Department at the Idaho State University has been cooperating with our center in performing more experiments to characterize flexible aerospace structures.

B.2. Current Focus

B.2.1. Modeling, Analysis, and Design of Highly Flexible Structures

We will extend the capability of GESA by adding design optimization and post processing modules. To make GESA available for use in multidisciplinary research, we will program it in module modes.

The finite-element code GESA will be a good teaching and research tool for nonlinear structural analysis. GESA can be used to analyze and design highly flexible deployable space structures such as dish antennas, solar array panels, tethering cables, and triangular zip booms, which are used by the NASA Johnson Space Center and Langley Research Center. Moreover, since the structural elements of GESA are displacement-based, they can be easily added as a new family of geometrically-exact structural elements to NASTRAN and/or the CSM testbed software system of the NASA Langley Research Center.

B.2.2. Analysis and Design of Smart Surface Structures for High-Speed Aircraft

We will study the nonlinear flutter dynamics in detail by using the concepts of modern nonlinear dynamics, such as modal interactions, bifurcation theory, Lyapunov exponents, and Chaos. We will investigate the use of elastic bending-torsion coupling of composite structures to passively change the flutter characteristics and to increase flutter speed. We will also investigate the suppression of flutter using nonlinear energy transfer mechanisms, such as internal resonances and saturation phenomenon by using piezoelectric actuators and sensors. These studies will provide results for determining the validity of the flexible-wing concept, which is the current major research topic of the Flight Dynamics Directorate at the Wright Laboratory.

B.2.3. Damage Detection and Health Monitoring of Aircraft Substructures

Several vibrometry techniques for health monitoring of large structures have been developed and tested. A novel approach using Transmittance Functions (TF) is currently being tested and has successfully detected small damages, such as delamination in a composite beam and loosening of bolts in an aluminum rib-stiffened panel. A transmittance function is a ratio of response quantities and can also be defined for a closed-loop actively controlled structure. In the Transmittance Function Monitoring (TFM) technique, no structural model is needed, input vibration does not need to be measured, damage can be detected on-line using random ambient excitation, the non-resonant part and zeros of the TFs can detect small damage such as cracks, and structural changes due to environmental effects are canceled in a TF. The TFM technique will be able to detect and locate delaminations, impact damage, moisture absorption, and voids in laminated and resin transfer molded composite structures.

We will improve the accuracy and efficiency of these techniques for structural damage identification and health monitoring using advanced signal processing techniques and efficient computational methods. We will investigates applying higher order signal processing techniques such as bi-spectrum analysis to further improve the accuracy of the technique. Moreover, we will develop an integrated system for active vibration suppression and simultaneous damage detection using piezoceramic sensor/actuator systems distributed over the structure.

The Structural Mechanics and Control (SMC) research laboratory will be expanded to support this research by purchasing a Scanning Laser Doppler Velocimeter (SLDV) to be able to quickly scan large structures for damage using our developed Transmittance Function Monitoring (TFM) algorithm.

B.2.4. Static and Dynamic Experiments on Flexible Structures

We will perform more experiments on the static and dynamic characteristics of composite and flexible structures at the Structural Mechanics and Control (SMC) research laboratory. The established data base of structural components will be documented for further use in design and control of aircraft structures. Specifically, we propose to characterize sandwich plates and shells, thermo-inexpensible composite structures, swept tapered isotropic and composite cantilevered plates (simulating aircraft wings), composite laminate-repaired aluminum plates, thin-walled beam, active thin-walled structures, and to investigate the influence of temperature on such structures. We will also test and document post-buckling load-carrying capacity, static and dynamic stabilities, and deployability of flexible structures.

C. AREA PROGRAM ACTIVITIES

C.1. Personnel

Dr. Pai joined North Carolina A&T State University and started coordinating the structures group of NASA-CORE on January 5, 1994. Dr. Schulz joined the Structures Group in the 1994 fall semester. Dr. Dunn joined both the Structures Group and the Control Group in the 1994 fall semester. Dr. Ahmad S. Naser joined the Structures Group as a research associate in May, 1995. He is in charge of the Structural Mechanics and Control Research Laboratory.

C.2. Education

The following three courses are directly related to the analysis and design of aircraft and were taught by Dr. Pai during 1994:

1. MEEN 422: aero vehicle structures
2. MEEN 580: aerospace vehicle design
3. MEEN 578: flight vehicle performance

The following two seminars are related to the research of structures and were given by Dr. Pai during 1994:

1. "Nonlinear Structural Vibrations" Mechanical Engineering Seminar, NCA&TSU, 1994.
2. "What Can We Do about HSCT?" NASA-CORE, 1994.

The following three courses are directly related to the analysis and design of aircraft and were taught by Dr. Pai during 1995:

1. MEEN 422: aero vehicle structures
2. MEEN 580: aerospace vehicle design
3. MEEN 578: flight vehicle performance

The following seminars were given by Dr. Naser during 1995:

1. "Random Vibrations of Composite Beams and Plates," Mechanical Engineering Seminar, NCA&TSU, October, 1995.
2. "Modal Analysis of Continuous Systems," Control Group of NASA-CORE, Nov. 9, 1995.

The following two courses are directly related to the analysis and design of aircraft and were taught by Dr. Pai during 1996:

1. MEEN 580: aerospace vehicle design
2. MEEN 578: flight vehicle performance

The following seminars were given by Drs. Pai, Schulz, and Naser during 1996:

1. "Piezoceramics for Control and Damage Detection in Aerospace Structures," ASM and ASME Meeting, North Carolina A&T State University, Greensboro, NC, Nov. 7, 1996.
2. "Structural Mechanics, Control, and Health Monitoring Research at North Carolina A&T State University," Sandia National Laboratories, Albuquerque, NM, Nov. 5, 1996.

C.3. Travel

1. First Industry/Academy Symposium on Research for Future Supersonic and Hypersonic Vehicles, Greensboro, North Carolina, Dec. 4-6, 1994 (Drs. Dunn, Pai, Schulz, and Shen).
2. "Parallel-Vector Methods for Computational Mechanics," Greensboro, North Carolina, December 1-2, 1994, a two-day short course (Drs. Pai, Schulz, and Shen).
3. The 31th Annual Technical Meeting, Society of Engineering Science, Texas A\&M University, Oct. 10-12, 1994 (Dr. Shen).
4. The IASTED International Conference on Modeling, Simulation and Identification, Wakayama, Japan, Sept. 12-16, 1994 (Dr. Shen).
5. Fifth Conference on Nonlinear Vibrations, Stability, and Dynamics of Structures and Mechanisms, Blacksburg, Virginia, June 12-16, 1994 (Drs. Pai and Schulz).
6. The SPACE94--the 4th International Conference on Engineering, Construction, and Operations in Space, Albuguerque, New Mexico, Feb., 1994 (Dr. Shen).
7. Fifteenth Canadian Congress of Applied Mechanics CANCAM '95, University of Victoria, Victoria, Canada, May 28-June 1, 1995 (Dr. Pai).
8. Tenth VPI&SU Symposium on Structural Dynamics and Control, Blacksburg, Virginia, May 8-10, 1995 (Drs. Schulz and Pai).
9. International Conference on Structural Dynamics, Vibration, Noise and Control, Hong Kong, Dec. 5-8, 1995 (Dr. Shen).
10. The 10th Engineering Mechanics Conference, ASCE, Boulder, CO., May 21-24, 1995. (Dr. Shen).

11. The 36th AIAA/ASME/ASCE/AHS/ASC Structures, Structural Dynamics, and Materials Conference, Sheraton New Orleans Hotel, New Orleans, LA, April 10-13, 1995 (Dr. Pai).
12. Third International Conference on Composites Engineering, New Orleans, LA, July 21-26, 1996 (Dr. Pai).
13. Sixth Conference on Nonlinear Vibrations, Stability, and Dynamics of Structures, Blacksburg, Virginia, June 9-13, 1996 (Drs. Schulz and Pai)
14. AIAA Dynamics Specialists Conference, Red Lion Hotel, Salt Lake City, UT, April 18-19, 1996 (Drs. Pai and Schulz).
15. International Modal Analysis Conference, February 12-15, 1996 (Dr. Schulz).
16. Advanced Vibration Diagnostic and Corrective Techniques, Myrtle Beach, SC, May 9, 1996 (Drs. Schulz and Naser).

D. LEVERAGED FUNDING

1. New Techniques in Experimental Structural Dynamics Using A Scanning Laser Vibrometer, $139,539 (under negotiation), Department of Defense, 8/1/97--7/31/01.
2. Health Monitoring of Helicopter Rotor Systems, $24,976, Pennsylvania State University, 4/1/97--3/31/98.
3. New Techniques in Experimental Structural Dynamics Using A Scanning Laser Vibrometer, $195,498, Air Force Office of Scientific Research, 5/1/97--6/30/01.
4. Dynamic Modeling and Testing of HAWTs with Light-Weight Composite Blades and Integrated Sensors for Health Monitoring, $294,213 (under negotiation), National Renewable Energy Laboratory, Golden, CO, 2/1/97--1/31/00.
5. A Structural Damping Technique Based on Coupling Structures with Electronic Circuits, $257,000, Army Research Office, Research Triangle Park, NC, 4/1/96--3/31/99.
6. Structural Damage Detection Development for Aircraft Structures, $100,000, E-Systems, Greenville, Texas, 9/23/96--9/30/97.
7. Detecting Structural Damage Using Transmittance Functions, $19,600, Sandia National Laboratories, Albuquerque, NM, 7/1/96--9/30/96.
8. Modeling and Damage Characterization of Composite Repair Patches, $29,260, E-Systems, Greenville, Texas, 3/6/95--12/4/95.

Computational Fluid Dynamics Group

COMPUTATIONAL FLUID DYNAMICS RESEARCH

FINAL REPORT

Prepared for

Center for Aerospace Research
NASA Center of Research Excellence (NASA-CORE)
College Of Engineering
North Carolina A&T State University

by

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January 1997

SUMMARY OF ACTIVITIES AND ACCOMPLISHMENTS

A. RESEARCH

A.1. Development of New Approaches in Turbulence Modeling

The development of one-equation turbulence models that directly solve for the eddy viscosity has recently seen a renewed. Models of this type can be integrated in an efficient manner and do not require an explicit value for an outer layer length scale. The models have shown reasonably accurate solutions to complex subsonic/transonic flowfields. Recently, the approach has been extended to the supersonic regime and good agreement was obtained for three-dimensional flow involving crossflow separation. Discrepancies between model predictions and experimental data however persist, and we will continue the research to reduce or eliminate these discrepancies and extend the range of applicability of the model. The key research activities in this effort are:

a. Compressibility corrections to eddy viscosity or gradient diffusion-based turbulence models have been implemented. Both one-equation models of Spalart-Allamaras as well as that of Edwards-McRae and the standard two-equation k-ε turbulence model have been modified, and results have been successfully compared with experimental data for both mixing layers and wall-bounded flows. Future work in this effort includes comparison between these various modified models and extending their application to reacting flows.

b. "Eddy viscosity transport" turbulence modeling. Development of alternative turbulence transport equation for accurate computation of high speed, wall-bounded flows, including shock-boundary layer interactions with flow reversals (separated flows).

A.2. Mofication of existing turbulence models:

a. Compressible dissipation models for use in SPARK code with two-equation turbulence modeling investigation of the effect of pressure dilatation on the growth rates of mixing layers.
b. Compressiblity corrections to one-equation model and for both mixing layers and wall bounded flows.

A.3. Research aimed at improving CFD algorithm accuracy and efficiency for hypersonic flows

a. Development of a two-dimensional Navier-Stokes solver based on a diagonal implicit-nonlinear multigrid scheme
b. Extension of the above scheme to include five species continuity equations
c. Computation of radiative heat flux for hypersonic chemically reacting flows by using a multidirectional, finite-difference scheme for Euler equations

A.4. Development of methods for high speed aircraft configurations (Waverider Research

The waverider research program in the CFD Group seeks to develop a multidisciplinary design technique, which will provide hypersonic vehicle configurations for a wide range of missions. In this research program, an inverse design approach is adopted. Prior knowledge of the flow field is assumed, and a search is conducted for hypersonic configurations that satisfied the given flow field. In the process, the aerodynamic characteristics of each vehicle is determined, and optimum configurations are chosen according to a fixed set of predetermined rules, based on the anticipated mission of the resulting vehicle.

a. Improvement of the waverider design tool through the incorporation of a propulsion system and a nozzle after body
b. Design of a fuzzy logic controller for a waverider derived aircraft

A.4. Numerical simulation of jet in a cross-flow

The study involved numerical modeling of a normal sonic jet injection into a hypersonic cross-flow. The General Aerodynamic Simulation Program (GASP) is being used for the analysis. The potential application of this analysis is thrust vectoring of spacecraft. Experimental data, generated by Southampton University light piston compression tube, is being used to validate the numerical simulation. The data available consist of the wall pressure distribution in the region upstream of the injection. Full Navier-Stokes solutions of the flow field show good agreement with pressure data for the injection and non-injection cases for various injectants such as helium, nitrogen and argon.

B. COLLABORATIVE RESEARCH

B.1. NASA Langley Research Center (Hypersonic Airbreathing Propulsion Branch): Incorporation of Wall Function Algorithm in a PNS Code

Another ongoing collaborative research activity with Hypersonic Airbreathing Propulsion Branch of NASA Langley involves enhancement of a PNS code by incorporating a wall function algorithm based on defect stream function approach. The method involves patching an analytically obtained inner region of the boundary layer solution to a numerically determined solution of the outer region. Since the inner region is analytically determined, this eliminates the computational need to locally refine the grid to resolve the inner region to capture the flow physics. Unlike other wall function methods, the location of the match point is determined as part of the solution process.

The method has been successfully incorporated in the two-dimensional version of the PNS code. The outer region was computed using a Baldwin-Lomax turbulence model. The predictions for the wall shear stress based on the wall function approach agreed with experimental data, as well as with the inner region fine grid solutions obtained without the application of the wall function. Additional research to be done includes extension of the flat plate calculation to other configurations and comparison of heat transfer predictions with experimental data as well as with fully gridded CFD calculations. The key activities of the effort are:

a. Enhancement of a PNS code by incorporating a wall function algorithm, based on work of Barnwell and Wahls.
b. Inner region solved analytically.
c. Computation of the outer region ($y/\delta > 0.2$) by using turbulence models.

Completed Work - Results:

a. Method has been implemented in two-dimensional version of the code and is being tested for two-dimensional flows. Preliminary results have been obtained for a range of Mach numbers for flat plate flows.
b. Good agreement is seen between fully-gridded and wall function calculations. With the wall function, the calculations were 30 - 300 times faster.

c. Method will be extended to more complex configurations and to examine heat transfer predictions.

B.2. NASA Lewis Reseach Center: CFD Analysis of Bypass Duct and Strut Flows

The overall goal is to contribute to the optimized design of fan bypass systems in advanced turbofan engines such as the Advanced Ducted Propulsors (ADP). The objective is to perform numerical simulations of duct-strut interactions to understand the loss mechanisms associated with this configuration that is characteristic of ADP. These simulations complement an experimental study being undertaken at Purdue University. The research activity is part of the Advanced Subsonic Technology (AST) program which involves a NASA/Industry/FAA partnership with the goal of a safe and highly productive global air transportation system. The CFD group is using the NPARC code to perform the numerical simulations and has gained considerable experience in the use of this code. Grids needed for the initial solutions have been generated. Simulations are underway for a wing-body junction. The key activities of the effort are:

a. Investigate, numerically, the loss mechanisms in duct-strut interactions typical of advanced turbofan engines.
b. Contribute to optimized design of bypass system in advanced ducted propulsors.
c. Use NPARC (a NASA Lewis compressible flow code using flux-split algorithms) to simulate the flow field on the LeRC CRAY Y-MP.
d. Compare with experimental data based on study being undertaken at Purdue University.
e. Grids to be used have been generated using GRIDGEN, and simulations ofwing-body junction flow for code calibration are underway.

Completed Work - Results:

a. Preliminary results of the wing-body problem have been obtained and are being analyzed.

B.3. U.S. Air Force Academy

a. Enhance design of integrated hypersonic vehicle configurations by conducting joint CFD and experimental investigations on the waverider configuration
   i. Analyze forebody/inlet flow field.
   ii. Develop an aerodynamic data base for overall configuration.
b. Design and construction of a complete waverider model to be built and tested at USAFA.
c. CFD analysis on the model to be conducted at NCA&TSU.

Completed Work - Results:

a. This research effort resulted in a master's thesis: "The Effect of Angle of Attack on Flow Characteristics of a Biconic."

C. INTERDISCIPLINARY RESEARCH (with the Aerospace Structures' Group)

Thermal Deformation Of Aircraft Skin Panels (initial effort involved static coupling between CFD and Structures groups)

Flow conditions: Turbulent Compressible flow, adiabatic (initially flat) Surface
$M = 6.57$
$Re = 0.37 \times 10^6$/ft

Major Effects Of Very High Speed Flow

Surface temperatures become very high as a result of viscous dissipation:

1. A flat panel becomes curved.
2. As a result of change in shock structure, the flow field is altered.
3. Thermal stresses are increased.
4. Flutter characteristics of the panel are affected.

The CFD Group has given an estimate of surface temperature to Structures Group for use as input to their structures code, which will generate a converged response (the deformed panel shape). We are in the process of setting up GASP to perform a three-dimensional simulation over a wavy plate. Also, an extensive literature survey is being conducted to ascertain the feasibility of performing a dynamically-coupled calculation in the near future. Dr. Guru P. Guruswamy of the NASA Ames Research Center has in recent years been doing research in the area of fluid/structural/control interaction [Reference: User's Guide for ENSAERO - A Multidisciplinary Program for Fluid/Structural/Control Interaction Studies of Aircraft (Release 1), NASA Technical Memorandum 108853]. The CFD Group has recently obtained the latest version of code ENSAERO for use in connection with our effort to couple aerodynamic and structural analysis to study aeroelastic response of flexible aerospace structures. We have received funding from the NASA Dryden Research Center to start research in 1997 in the area of multidisciplinary modeling and simulation of aerospace vehicle systems. The work will involve the use of a multidisciplinary finite-element code, STARS, which was developed at NASA/Dryden. The code couples the fluid dynamics equations with the structural equations.

D. SUPERCOMPUTER USE

As a result of proposals submitted to the North Carolina Supercomputing Center (NCSC), researchers in the CFD Group have been awarded computer time in the 200-300 CPU Hours range each on CRAY Y-MP. Additionally, we have access to supercomputers at NASA Langley and NASA Lewis Research Centers through internet connectitivity. The CFD Group has twelve Silicon Graphics, Inc. (SGI) high-end workstations, including a two-processor Power Onyx, for use by research faculty and students.

E. EDUCATIONAL EFFORT

E.1. Graduate Courses

The following graduate courses were offered to students in 1995 and 1996 calender years:

Semester	Course	Instructor
Spring 1995	Boundary Layer Theory	Chandra
Fall 1995	Computational Fluid Dynamics	Daso
	Convection Heat Transfer	Chandra
Spring 1996	Conduction Heat Transfer	Daso
	Advanced Fluid Dynamics	Chandra
Fall 1996	Thermal Radiation Heat Transfer	Daso
	Boundary Layer Theory	Chandra

E.2. Summer Ourtreach Programs: Faculty/Students At NASA Field Centers

1. Cheryl Sellers (Summers of 1991 and 1992 at LaRC)
2. Damon Jeffries (Summer of 1994 at Ames)
3. Dr. Kenneth Jones (Summers of 1994 and 1995 at Marshall; Summer 1996 at LeRC)
4. Dr. Suresh Chandra (Summers of 1991 and 1992 as well as continuing contacts at LaRC)

E.3. Proposed Computational Fluid Dynamics Laboratory

The laboratory is being set up in the new Edward B. Fort Interdisciplinary Research Center. The laboratory consists of several SGI high-end workstations, including a two-processor Power Onyx, as well as a two-processor Sun Microsystems Sparcstation 2 workstation. Other support equipment in the CFD laboratory include one personal computer, a network printer and a color scanner for research and technical work.

F. EXTERNAL AND LEVERAGED FUNDING

1. NASA Lewis Research Center ($240,000 over three years)
2. U.S. Air Force Academy ($38,000 for Summer, 1995)
3. NASA Langley Research Center (Expertise + Computer time)
4. NASA Dryden Flight Research Center ($99,998 for 1997)
5. 8 Proposals were submitted to aerospace industry, DoD and other research institutions.

Controls and Guidance Group

CONTROLS AND GUIDANCE RESEARCH

FINAL REPORT

Prepared for

Center for Aerospace Research
NASA Center of Research Excellence (NASA-CORE)
College Of Engineering
North Carolina A&T State University

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A. BASIC RESEARCH

The main activities of the Control and Guidance Group are in the areas of linear and nonlinear controls. We discuss the work accomplished from January 1992 to December 1996 in basic, applied, and experimental research areas. In this area, we considered many aspects of intelligent control systems theory. We have especially considered issues of optimizing classical and fuzzy controllers using genetic algorithms, and issues of organizing different control methodologies in hierarchical and hybrid schemes.

A.1. Tasks Completed

1. We developed a new method of designing the membership functions and rule sets of fuzzy controllers simultaneously using genetic algorithms[1, 19,37, 38 and 39]. Previous work using genetic algorithms has focused on the development of rule sets or high-performance membership functions; however, the interdependence between these two components suggests a simultaneous design procedure would be more appropriate. When GAs have been used to develop both, it has been done serially, e.g. design the membership functions and then use them in the design of the rulebase. We used to design complete fuzzy controllers given the equations of motion of the system. This new method was applied to two problems, a cart controller and a truck controller. We also examined the design of a robust controller for the cart problem and its ability to overcome faulty rules.
2. We developed and investigated using genetic algorithms for the automation design of hierarchical hybrid fuzzy-PID controllers of two-link robotic arms[4,5]. Traditional methods of designing FLCs are based on expert heuristic knowledge and trial and error, and are often tedious and unyielding. We developed a computer-implemented procedure to designing a Hierarchical Hybrid Fuzzy-PID (HHFPID) controller for the position and trajectory control of a two-link robotic arm. This procedure combines genetic algorithms (GAs), expert knowledge, and fuzzy learning from examples. We have discussed the computational issues of our approach, and the design of fitness functions and encoding schemes required by the genetic algorithms. Based on extensive simulation studies, we concluded that the GA-designed controller has a satisfactory and sometimes superior performance.
3. We developed a new method of solving nonlinear-constrained optimization problem using genetic algorithms with penalty functions[17]. This work presents an application of genetic algorithms to nonlinear constrained optimization. This extension is based on systematic multi-stage assignments of weights in the penalty method.
4. We developed a fuzzy inference engine to reduce the chattering of variable structure control using genetic algorithms[23, 26]. Today's technology requires controls capable of handling highly nonlinear, time-varying, and uncertain systems. Variable structure control is one such control method. Variable structure control (VSC) is invariant to system perturbations and external disturbances; however, a high frequency control chattering exists which renders the VSC impractical for most applications. Fuzzy inference is used to reduce the chattering. By using fuzzy inference to determine the switching scheme of the VSC, the original robustness and fast response time of the VSC is retained while reducing the control chattering. Optimization of the fuzzy parameters using Genetic Algorithms was also produce a system with improved response time and accuracy.
5. We investigated a theoretical justification for the nonlinear control property of a class of fuzzy logic controllers[27]. In a previous work[20, 25], a hybrid implementation of fuzzy and conventional PID controller was introduced and its application to a 2-degree of freedom robot manipulator arm was examined. A theoretical justification for that approach, based on the fact that "fuzzy systems are universal approximators" is presented in this work.
6. We investigated the role of hierarchy in the design of fuzzy logic controllers[3]. Also, hierarchical learning-based design of a hybrid fuzzy PID controller was developed[9]. This study investigates the role of hierarchy in the systematic approach to the design of fuzzy logic controllers (FLCs). The key concept here is that the implementation of fuzzy engines at higher

levels of the control hierarchy (where more reasoning is involved) yields more versatile fuzzy controllers with generally fewer control rules. At the same time, the structured nature of a hierarchical approach considerably simplifies the design procedure.

B. EXPERIMENTAL RESEARCH

We have built a vibration testing and control laboratory. Our main experimental setup consists of a thin plate fabricated with clamped boundary conditions. It is made of .050 inch thick 5052 aluminum sheet. The plate is horizontally oriented and is sandwiched between two frames, each made from 1 inch thick 6061 aluminum. The plate measures 28 inches by 21 inches. The external vibrations are introduced through a shaker mounted beneath the plate. Miniature accelerometers (PCB Model 352B22 mini-shearcel) are used to sense the state of the system. Piezo-ceramic actuators, mounted above and below the plate to induce a pure bending moment, provide the active control. At present the rate feedback controller is being implemented, with a Hybrid Fuzzy PID controller coming next. All control algorithms are implemented in LabVIEW (National Instruments) using the native LabVIEW programming language (G) or using a code interface node to existing C code.

The study objective is to actively reduce the level of vibration in the plate. This problem has been well documented in the literature from the standpoint of linear controllers and so provides an excellent reference point to existing control strategies. These control strategies, including rate feedback and H_2/H_∞ have demonstrated acceptable performance when the model is well known but lack a certain amount of robustness when the model is uncertain. Our Hierarchical Hybrid Fuzzy PID (HHFPID) controllers have demonstrated excellent robustness in the face of such model and parameter uncertainties in simulation. The experimental results forthcoming from the plate experiment should add further weight to our robustness claims. The use of a hierarchical structure has already demonstrated superior performance when the hierarchy is based upon a subdivision of the controller's input space. We are exploring the use of a hierarchy based upon multiple performance objectives.

C. APPLIED RESEARCH

The basic research topics discussed in sections 2.1 and 2.2 have been applied to various systems, specifically to the aerospace systems and a two link robotic arm. Some of investigations include control, estimation, fault tolerance, tracking, eigenstructure assignment etc. The details are available in the papers listed in the publications.

C.1. Controls

Tasks Completed

1. We designed a variable structure control for discrete-time systems[2]. This work presented a treatment of discrete-time variable structure control systems. The purpose was to lay a foundation upon which design of such type of systems can be made properly. Phenomena of switching, reaching, and quasi-sliding mode were investigated thoroughly. Methods of quasi-sliding mode design were given. The inherently existing quasi-sliding mode band were analyzed. A recently introduced "reaching law approach" was conveniently used to develop the control law for robust control.
2. We designed fuzzy controllers for the autonomous rendezvous and docking problems[5]. Autonomous rendezvous and docking problems have been defined as one of the primary goals in today's space technology. Autonomous operation of an unmanned space vehicle in a real-

world environment poses a series of problems. The knowledge about the environment is in general incomplete, uncertain and approximate. Perceptually acquired information is not precise, sensor noise introduces uncertainty, and the sensor limited range and visibility introduces incompleteness. In this study, fuzzy logic and genetic algorithms have been applied to this problem in order to perform better in the case of all these problems.

3. We designed a genetic algorithm approach to the search for golomb rulers[6]. The success of genetic algorithm in finding relatively good solutions to NP-complete problems such as the traveling salesman problem and job-shop scheduling provided a good starting point for a machine intelligent method of finding Golomb Rulers. These rulers have been applied to radio astronomy, X-ray crystallography, circuit layout and geographical mapping. Currently the shortest lengths of the first sixteen rulers are known. The nature of NP-completeness makes the search for higher-order rulers difficult and time consuming. While the shortest lengths for each order are important as a mathematical exercise, finding relatively short high-order valid rulers has a more important impact on real-world applications. Genetic algorithms have shown good results in finding usable Golomb Rulers in minutes or hours instead of weeks or months.
4. We designed lateral vehicle guidance control law by fuzzy logic control[7]. A Fuzzy rulebase controllers implemented in a vehicle to control the lateral guidance for an automated highway system. Based on human drivers' experiences, the fuzzy rules were designed to keep the vehicle in the center of a given lane. The controller allows the vehicle to track the center of a given lane within a 0.2 meter tolerance.
5. We optimized turbofan engines design using genetic algorithms[16]. This work presents an application of genetic algorithms to the system optimization of turbofan engines. In order to characterize the many measures of aircraft engine performance, two different criteria are chosen for evaluation. These criteria are thrust per unit mass flow rate and overall efficiency. These criteria are optimized using four key parameters including Mach number, compressor pressure ratio, fan pressure ratio, and bypass ratio. After observing how each parameter influences objective functions independently, the two objective functions were combined to examine their interaction in a multi-objective function optimization. Numerical results indicate that genetic algorithms are capable of optimizing a complex system quickly. The resultant parameter values agree well with previous studies.
6. We completed a parallel design of membership functions and rule sets for fuzzy controllers using genetic algorithms[19]. For more information please see task I of section 2.2.
7. We designed a fuzzy controller for robotic arms[24,25]. Regardless of the application domain, the main idea is to convert a linguistic control scenario into an automatic control strategy. The expert's knowledge is the backbone of this linguistic control strategy. FLCs have had their most successful implementations where the process under control is too complex for analysis by conventional quantitative. This work proposed a "hybrid" implementation of FLCs and conventional PID controllers which can be helpful in some applications. The proposed method is applied to a two-degree-of-freedom robot arm with promising results.
8. We optimized spacecraft spin axis attitude determination via real-value genetic algorithm [28]. This study treats the problem of spacecraft spin attitude determination from a set of noisy measurements. A genetic algorithm approach was used to solve this type of problem. The motivation behind employing the GA stemmed from the fact that under measurement noise, many of the existing methods in literature were either not applicable or tend to require some problem-specific fix. It is shown that the GAs are effective for this type of nonlinear constrained-optimization problems because of their generality and robustness. Simulation and comparison of results to previously existing methods were conducted on a practical numerical problem. The results agreed very well with those of existing methods. The robustness of the GA methods was clearly shown in the presence of noisy measurements.
9. We achieved continuous output tracking of a class of nonlinear systems by a fuzzy controller[29]. The tracking control problem of a class of nonlinear systems utilizing a hybrid fuzzy-PID (HFPID) controller was addressed. The particular class of problem considered is descriptive of many practical problems encountered in Electrical and Mechanical Engineering. The implementation of HFPID control requires fewer restrictive assumptions about the system

and needs no change in procedure to deal with parameter uncertainty and external disturbances. The application of the proposed strategy to the suppression of vibration in a two-bay flexible truss-structure was presented.

10. We achieved fault detection in aircraft engine using an eigenstructure analysis[35]. The traditional method of fault detection known as hardware redundancy, involves an odd number of sensors (minimum three), which are used to detect the occurrence of a fault. Readings of these sensors are fed to a majority voter, the output of which indicates the occurrence of a fault. It is desirable to have a fault-detection system, which does not suffer from the inherent weaknesses of the above scheme, namely space limitations aboard the aircraft, and exposure of all the sensors to the same environment. In this work, we proposed an analytical approach to fault detection, and a fault detection and isolation (FDI) system, which is based on three or more dissimilar sensors.
11. Designed a fuzzy controller of VSTOL aircraft longitudinal axis[33]. Hybrid Fuzzy-PID (HFPID) control, consisting of a fuzzy engine that designs the coefficients of a conventional PID controller, was applied to the control of the longitudinal axis of a VSTOL aircraft. The control of the longitudinal axis is a nonlinear problem complicated by the transition from hover to normal flight required by a VSTOL aircraft. This transition region may introduce singular matrices not usually encountered in a normal flight regime, hence requiring existing techniques to be compensated.
12. Quantified MRI brain images using genetic algorithms[36]. This work addressed the usage of Genetic Algorithms (GAs) to automatically quantify the three types of brain tissue, cerebrospinal fluid (CSF), white matter, and gray matter. The quantification technique utilizes a statistical model of the noise and partial volume effect and fits a derived probability density function to that of the data. The results were compared with those obtained by a tree-annealing algorithm.
13. We developed a methodology for guiding the longitudinal motions of the space shuttle orbiter during atmospheric reentry using Sugeno fuzzy approximations[43]. One of the major concerns of the Space Shuttle Orbiter guidance system is to achieve atmospheric reentry without violating state and control constraints. The orbiter guidance law is required to track this profile using bank-angle maneuvers. This research is also relevant to the new Advanced Crew Recovery vehicle intended for use with the Space Station. Currently, a neighboring linear guidance law that is scheduled on a single variable (velocity) is used. We use Sugeno approximators (a hybrid fuzzy-crisp inference engine) to conduct the interpolation. The Sugeno approximators are trained by example using a recursive least-squares algorithm similar to a static Kalman filter. Another contribution is to introduce the concept of Surface-Tracking guidance (or control), to be contrasted to the familiar trajectory tracking, and to implement it using Sugeno approximators. This is a difficult optimization problem which is also solved using Sugeno approximations.

C.2. Nonlinear Optimal Control

One of the objectives of the control group in the area of nonlinear optimal control was to develop optimal trajectories and guidance for a hypersonic type of vehicles. The work described in this part pertains to our effort in developing an advanced control strategy for such systems.

Tasks Completed

1. Designed a nonlinear adaptive robust control law for an uncertain flexible spacecraft[21]. We began by addressing the tracking problem for a class of nonlinear dynamic systems with modeling uncertainties and external disturbances. New control algorithms that accommodate modeling uncertainties were proposed. It was shown that these algorithms not only guarantee system stability but also achieve a certain bounded performance index and were readily applicable in vibration suppression of large flexible space structures. Numerical verification of

the proposed strategy was demonstrated via the lumped mass model of a hypersonic aerospace flight vehicle structure.

2. We investigated suppression of critical-mode vibrations in large flexible space structures (LFSS)[22]. Based on the structure property of an LFSS, an active damping strategy was proposed to effectively attenuate the critical vibrations of the structure subject to modeling uncertainty and external disturbances. Control algorithms were derived with the aim of suppressing both the vibrating magnitude and vibrating rate to an acceptable level. It was shown that the strategy exhibits robust and adaptive properties and was truly model-independent. The novelty of the proposed approach lies in the fact that it was fairly easy to set up the strategy and the overall computation involved was much less than any other strategies available to date. A two-bay truss was used to verify the validity of the proposed approach.
3. We investigated control of flexible space structure via compensated inverse dynamics approach[18]. The motivation for the study stems from the need to control practical systems arising from aerospace and mechanical engineering. Because modeling uncertainties and external disturbances are always present in these systems, the inverse dynamics technique is not applicable directly. A compensated inverse dynamics approach was proposed to account for the effect of uncertainties. The compensation is achieved by adaptive and robust schemes. application of the proposed strategy to the vibration suppression of a two-bay flexible truss structure was presented.
4. We designed robust motion tracking control of robotic arms based on the generalized energy accumulation principle[40]. Criteria for system stability and performance analysis were established in the first part of this work[8]. These criteria were of immediate use in many systems. The main purpose in this part of the work was to apply these criteria to Robotic systems. Both adaptive and robust control were investigated.
5. We studied system stability and performance analysis based on generalized energy accumulation[41]. This work was concerned with the control problem of a multi-robot system handling a payload with unknown mass properties. Force constraints at the grasp points were considered. Robust control schemes were proposed that cope with the model uncertainty and achieve asymptotic tracking. To deal with the force constraints, a strategy for optimally sharing the task was suggested. This strategy basically consists of two steps. The first detects the robots that need help and the second arranges that help. It was shown that the overall system was not only robust to uncertain payload parameters, but also satisfies the force constraints.
6. We designed a nonlinear robust controller for multi-robotic systems with unknown payloads[42]. This work investigated a control strategy that was simple to implement, easy to code for programming and robust to time-varying uncertainties. The proposed robust control law were not based on q, q' and p, but on the desired path {q*, q'*} and parameters p* which can be precomputed off-line. Also one does not need to re-organize the robotic dynamics before calculating the control torque. By setting H* = 0, C* = 0, and G* = 0, the control torque reduces to *tau* = -KW + U, leading to a simple way to control the system.

C.3. Linear Optimal Control

In the area of linear control, the inverse problem of linear-quadratic regulators was addressed using Bode plots of a loop transfer function. Analysis with Bode plots helps to identify a loop transfer function for guaranteed stability margins. We are presently extending this research to address previewed control with output feedback. Also, with real parametric uncertainties in a controllable pair, the pole assignment problem is discussed.

Tasks Completed

1. Analyzed the inverse problem of Linear Quadratic (LQ) controllers using Bode plots[10]. Let A and B be the matrices representing a linearized system with respect to an operating point. Suppose K is a stabilizing controller for the controllable pair (A,B). In this work, we

addressed necessary and sufficient condition for the controller K to be LQ optimal. We used the Bode plots of the loop transfer function $h(s) = K(sI - A)^{-1}B$ to decide optimality. The result states that the controller K is LQ optimal if and only if the magnitude and phase plots of $h(j\omega)$ at all frequencies ω, satisfy:

magnitude of $h(j\omega) \geq -2$ *cosine(phase of* $h(j\omega)$*)* $\forall\ \omega > 0$

Analysis in this setting is useful to design a minimal-order controller without loop transfer function recovery, which is an estimation-based design procedure.

2. We developed approximate quadratic weights for previewed flight control[11]. This work is an application of the result discussed in the above item. The loop transfer recovery based design procedure for inner loop controller of Boeing 757 model is compared with a simple static gain output feedback controller. For this controller in the sensor loops, we also guarantee the existence of a positive definite solution matrix (PDSM) to the Algebraic Riccati Equation. That is, if the turbulence and wind gusts during flight cruise are measurable, the need of a PDSM to compute the supplemental elevator deflections for smooth ride quality is discussed. We assume LIDAR measurements to preview the time of occurrence and intensity of turbulence.
3. We developed supplemental elevator deflections required for robust flight cruise in turbulent time windows[14,15]. While designing supplemental elevator deflections for normal acceleration based ride quality, should we include the long period modes in design model. In this work, short-period model based design is analyzed for the model with both short and long period modes[15]. Further, the dependency of LIDAR measurements on the supplemental elevator deflections at a given time instant is investigated, when we intend to compute such deflections at other time instants[14].
4. We analyzed aircraft pitch control with fixed-order LQ compensators[12]. We used the concept of selecting controllers when minimal overshoot is desired in time response. This problem is studied using LQ formulations.
5. We investigated a design procedure for pole assignment in linear uncertain systems[13]. Linear models at every point in a flight envelope are known to represent a complex nonlinear aircraft. If we wish to have a single controller for a family of linear models (that is, for a sub-region in the flight envelope), then we assume that the sub-region is an uncertain system with matrices $(A + \Delta A, B + \Delta B)$ where the elements of matrices ΔA and ΔB represent aerodynamic coefficients varying in a given interval with specified upper and lower bounds. For this family of linear models, a controller K is designed such that the eigenvalues of $[A + \Delta A + (B + \Delta B)K]$ reside in a given set of circular regions. By restricting the eigenvalues in circular regions, we preserve the controlled aircraft's stability and performance, when it operates over any flight condition in the sub-region.

C.4. Flutter and vibration modeling of an aircraft wing was studied.

Tasks Completed

1. An Algorithm for Extracting Cycle Sequences From Variable Amplitude Load Histories[30] was developed. The algorithm logic for extracting variable amplitude/irregular load histories cycle sequences was presented. The result is a linked list data base file. The link list quantitatively gives cycle sequences for cyclic loaded engineering alloys. The algorithm extends prior rainflow cycle counting procedures. By considering qualitative engineering alloy behaviors first, improvements may be possible in quantitative fatigue and cyclic mechanical stress-strain predictions.

D. EDUCATIONAL EFFORT

E.1. Courses

The following courses are supported by the center and are taught every semester.

1. ELEN 410: Linear Systems and Control
2. ELEN 668: Automatic Control Theory

D.2. Control Systems Laboratory

We have also developed a Control Systems Laboratory. Laboratory space has been assigned, and many basic control testbeds have been purchased, such as the inverted pendulum, PID modules, torsional spring control, etc.

Human-Machine Systems Engineering Group

HUMAN-MACHINE SYSTEMS ENGINEERING RESEARCH

FINAL REPORT

Prepared for

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NASA Center of Research Excellence (NASA-CORE)
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PROGRAM SUMMARY

Numerous studies of human performance in mental and physical task handling qualities were performed. A prototype in-house, physical platform simulator was designed, built, and used in the experiments, as were scaled-down supervisory control tasks. The studies were concentrated on the effects of motion and dynamic orientations of human subjects in performing supervisory control tasks. The primary dependent variables were workload, human performance, and human response to task dynamicities induced by motion or position orientations. Our results show the following: (a) Cue delay times combined with postural orientation influence human response to control tasks; (b) Different postural orientations affect both compensatory and pursuit tracking tasks; (c) Human performance can be predicted as a function of workload on the Cooper-Harper subjective scale; and (d) Task dynamicity and complexity influence workload perception.

List Of Symbols

The variables used in the report of the this component are defined as follows.

AFSP	=	Aggie Flight Simulator Platform
P	=	Performance metric
X	=	Cooper-Harper rating scale value
WL	=	workload factor
QWI	=	Quantitative workload index
p	=	statistical level of significance (probability of Type I error)
R^2	=	Model fit coefficient
T_1	=	operator lead time
T_2	=	neuromuscular lag time
A(s)	=	signal step function
e(s)	=	error term
t_n	=	effective time delay
t_0	=	proprioceptive delay time
K_3	=	error correction (learning simplification term), $0 < K_3 < \infty$
K_1	=	model gain which is a function of signal bandwidth
K_2	=	plant gain
b	=	scaling factor associated with control task difficulty; b>u
K_n	=	feedback transfer function
R(t)	=	response time function
$G_F(s)$	=	feedback frequency function
t	=	signal time
ω_c	=	undamped natural frequency for task control
ω_n	=	undamped natural frequency for feedback control
γ	=	phase angle
ω_d	=	asymptotic gain crossover frequency which is due to feedback function
β	=	phase shift angle
C(s)	=	closed loop transfer function
K_4	=	K_3/b
g	=	"a" parameter
B	=	lead lag term = damping coefficient
α	=	amplification factor
s	=	Laplace parameter
$\lambda(s)$	=	characteristic Laplace function
K_H	=	arm/hand characteristic function
K_P	=	proprioceptive characteristic function
T_R	=	response time to incoming stimuli
T_M	=	arm/hand movement time; an approximation to decision initiation time
C_P	=	human element gain constant at the central in function processing-unit (an approximation to delay time factor)
τ	=	proprioceptive delay time
τ_n	=	neuromuscular delay time
a	=	complexity parameter
c	=	a hypothetical work content or load
$\Psi(s)$	=	input to the system, such as the command to the computer.
$G_P(s)$	=	the transfer function(describing function) of the human operator.

$G_C(s)$ = the transfer function(describing function) of the controlled element.

$N(s)$ = the transfer function of the disturbance, such as noise from the environment generated by mouse or computer sensors.

$E(s)$ = the error function.

DC = direct cues

LC = non-directed or latent cues

SC = signal cueing

S-R = signal-response

RT = response time

A. RESEARCH SUMMARY

A.1. Major Accomplishments

A.1.1. Technical

A physical motion-based platform simulator was designed, fabricated, and installed for expermental use in the Human-Machine Systems Engineering Laboratory. The simulator is called the Aggie Flight Simulator Platform (AFSP).

Research in the program led to the development of both mathematical and experimental models of the human operator in simulated flight and cockpit environments that mimic sonic-supersonic vehicle motions. Results obtained produced expected controller signal response times with position, velocity, and acceleration control tasks using the AFSP. Results are shown in Table 3.

Table 3. Expected controller signal time response

System	Response time (sec.)
Position control	$0.4 \pm 0.85\sigma,\ 0 \le \sigma \le 0.3$
Velocity control	$0.6 \pm 0.1\sigma,\ 1 \le \sigma \le 1.5$
Acceleration control	$0.5 \pm 0.12\sigma,\ 0.958 \le \sigma \le 1.25$

In Table 3, σ is the population standard deviation. The response time values consider the levels of learning (feedback error minimization and task complexity). In the time domain, the derived control signal time models yields the optimal control parameters seen in Table 4.

Table 4. Optimal Values by Simulation

ξ	ω_n	K_1	b	K_3
0.65	15.4	2.366	1.732	1
0.68	14.7	2.6	0.93	0.5
0.707	14.14	2	0.5	0.25
0.72	13.88	1.925	1	0.48
0.75	13.33	1.78	1	0.437
0.78	12.82	1.64	5.125	2
0.8	12.5	1.56	5.54	2
0.82	12.12	1.46	3.198	1.5
0.86	11.62	1.35	1.5	0.389

A.1.1.1. Human Performance in Motion Induced Vigilance and Control Tasks

Six different experiments were conducted to test whether unexpected motion turbulence has any impact on the human operator's response time. These experiments are described below. Unless otherwise noted, all significant results were obtained at an alpha level of 0.05.

A.1.1.1.1. Experiment 1

In the first experiment, human subjects were subjected to dynamic orientations at varying speeds (motion) on the AFSP. The objective of the study was to investigate whether there were any statistically significant differences in performance times at different levels of dynamic pilot orientation during manual control. Experimental results show that average response and movement times varied with orientation scenario. It was observed that both minimum average response and movement times occur at an orientation position with the subject at a pitch angle of 30°, roll angle of 30°, and yaw angle of 0°. The maximum average response time occurred at an orientation scenario of pitch angle of 30° and roll angle of -30°. The maximum average movement time occurred at an orientation scenario with a pitch angle of -30° and roll angle of 0°. Based on these results, it can be concluded that behavioral responses may be altered when the human body is in different spatial orientations. This could significantly impact manual control, thus potentially affecting flight handling quality.

Statistically, there exists sufficient evidence to conclude that postural position significantly affects response time. Also, there exists statistical evidence to conclude that postural position affects movement time. It is deduced that these results are due to the impact of an unfamiliar postural orientation on motor control, which may affect arm-motion dynamics and other biomechanical factors of the human operator. Additionally, all interactions (visual stimuli and cue delay) affect both response and movement times. In the context of the supersonic flight tasks, it is critical to recognize the impact of this environment on response times in the performance of remnant manual control tasks assigned to an operator during automation failure.

It was observed that the, in general, response time to an auditory stimulus was faster than to a visual stimulus, thus confirming earlier literature findings (Wickens, 1984). Statistically, there exists sufficient evidence to conclude that stimuli types affect both response and movement times. Additionally, the interactions with stimulus type significantly affects response times as well.

Experimental data show that as cue delay times increased, the average response time increased. Based on the descriptive statistical analysis, no trend was observed between average movement and cue delay times. It is found that the presentation of a warning, prior to stimuli, increased response time for vigilance. The increase of response times after 4 seconds may need further validation. This is reinforced by the observation that a cue delay time of 4 seconds under a light stimulus provided minimum response time. It is noted that a minimum response time occurred with a cue delay time of 10 seconds under an auditory stimulus. Based on this observation, it can be concluded that an auditory stimulus, independent of cue delay, provides for increased human vigilance. This conformed to results found in earlier studies by Young, et al. (1964). It was concluded that cue delay times significantly affect response time. In line with observations made based on the descriptive statistics analysis, it was also concluded that cue delay times do not significantly affect movement times. Also, the interactions of cue delay and the other factors significantly affected response time; and postural orientation with cue delay interactions, independent of stimuli, affected movement time (Winchester, 1994).

A.1.1.1.2. Experiment 2

The objective of the second experiment was to study human response errors as a function of dynamic postural orientations and induced motion on the AFSP. The analysis was performed using decision theory and reliability models. The paradigm was to uncover people's preferred sitting orientations during task executions. Costs were associated to errors committed due to a failure to respond to either visual warning signals, auditory warning signals, or both visual and auditory warning signals presented simultaneously. Statistical results found using ANOVA showed that: (a) the human errors were different for stimuli types (auditory and visual signals); (b) people have unequal chances of committing errors at different orientations; and (c) they responded differently to the signal cues. These results confirmed the findings of Schum and Pfeiffer (1973) and Johnson et al. (1973): errors committed by human controllers can be used as a utility model to optimize position and rate control designs. In the AFSP domain results showed that, on the average, the subjects preferred an orientation situation with pitch angle of -30°, roll angle of -30°, and yaw angle of 0°. This orientation generated the lowest expected error cost (Smith, 1995).

A.1.1.1.3. Experiment 3

In this study, the effects of prolonged sitting on mental task performance were researched (Pitman and Ntuen, 1996). The pilot is a sedentary worker relegated to the seated position, frequently for prolonged periods of time. Automation has particularly captured the interest of the aviation industry, where the pilot is being delegated to the role of system monitor rather than the decision maker for which he/she was previously selected and trained.

A review of the literature on prolonged sitting shows the effects of both biomechanical and physiological stressors. The normal shape of the spine is a compound curvature and is seen when a person is standing erect. The shape of the spine is altered when a person sits which increases pressure on the intevertebral discs. Studies by Nachemson & Morris (1964), Okushima (1970) and others have confirmed that intevertebral disc pressure is 35% lower when standing than when sitting. Reasons for this include an increase in the trunk load moment and the deformation of the disc caused by lumbar spine flatting (Andersson, 1974).

Physiologically, Calliet (1973) showed that the spinal alterations during sitting also create a process of isometric contraction of the paravertebral muscles. Prolonged isometric contraction causes endomuscular pressure which restricts blood flow, resulting in ischemia. Not only do muscles become fatigued, stress may be transferred to other soft tissues.

Stress is often viewed as a force that degrades performance capability (Hancock and Warm, 1989). Stressors can be environmental (i.e., heat, noise, work-rest schedule) or cognitive (i.e., boredom and pressure). The fatigue and discomfort associated with prolonged sitting is considered an aspect of the environment. As the level of fatigue or discomfort increases with periods of prolonged sitting, there may be a shifting of attention from task performance to the mitigation of discomfort, i.e., attempts to change posture within the seating constraints, or "restlessness". It would seem that these environmental demands have the potential to degrade performance as demands for attention are shifted away from the task at hand.

Previous studies of stressors on task performance relating to the physical environment examine the effects of such extremes as heat, humidity, and whole-body vibrations (see Davis and Parasuraman, 1982, for a review). Bhatnager, Drury and Schiro (1985) studied the effect of posture on performance in an industrial inspection task. In this study comparisons were made between various postural configurations. Kopardekar and Mital (1994) looked at the optimal work-rest schedules for directory assistance operators at computer workstations. The intent of the study was to determine a work-rest schedule to optimize operator performance. These studies allowed for unrestricted postural changes during the rest breaks allowed under the test conditions, thus allowing for both physical and mental recovery. However, no previous research has considered the effect of prolonged seated posture as a stressor which can effect performance.

In this study, we hypothesized that prolonged sitting may be associated with a decline in performance when performing a vigilance task. It was hypothesized that response time in responding to critical signals within the system would increase during sequential trials of a system monitoring task when body posture is constrained to the seated position.

Subjects monitored a VGA video display terminal controlled by an IBM compatible computer. The screen display was the Multi-Attribute Test battery (MAT) designed by NASA-Langley Research Center. The test presented multiple tasks such as system monitoring, pursuit tracking, and resource allocation which simulate those tasks performed by the pilot in the cockpit. Subjects responded by striking keys on a standard IBM-compatible enhanced keyboard. Subjects were seated in a chair with adjustable back height (lumbar support) and seat height.

All subjects participated in 4 sequential 30 minute vigils with a 10 minute break between trials. During the breaks the task was removed; however, subjects were required to remain seated. The task consisted of the system monitoring portion of the MAT. Subjects monitored two light displays and four floating scales. Response times (RT) were measured for lights and gauges during each trial. Results showed an upward trend across trials, confirming our hypothesis.

There also appeared to be a difference in the RT_{lights} as opposed to RT_{dials}, with RT_{lights} being greater. Previous research on attention (Wickens, 1987) suggest this may be attributed to the signal rates of change. The scales provided continuous movements throughout the experiment; however, changes in light displays occurred approximately once each minute. Subject scanning techniques may have focused more on the continuous movement of the scales.

A.1.1.1.4. Experiment 4

This was a field experiment conducted to validate some of the findings of Experiment 3. Several commercial airline pilots participated in a series of interviews and surveys which concluded that the problem was not the placement of instruments within the cockpit but the scheduling and comfort of the flights. Therefore, it is important to address the pilot's concerns in addition to new technology incorporated into the cockpits.

The interviews and surveys administered were used to determine the percentage levels of fatigue experienced by pilots while on duty. It was concluded from the interviews and surveys that there are four types of fatigue which can affect a pilot's ability to fly. These are:

a) Monotony fatigue : 30%;
b) Circadian fatigue : 26%;
c) Chronic fatigue : 22%; and
d) Visual fatigue : 22%.

The pilots' ability to interact with the current automation and controls is essential to the safety of the passengers and crew aboard the aircraft. The cockpit design should be centered around the capabilities and functions of the pilot. A problem seen in the current automation within the glass cockpit is the tendency to cause confusion within the cockpit. It has been demonstrated through surveys and research that many of the experienced pilots of the automated aircraft are occasionally surprised by the systems reaction to non-routine flight conditions. For example, mode confusion occurs often in vertical navigation. An example of this confusion is when an auto-pilot system shifts from a vertical climb mode to altitude capture and then to altitude hold during leveling off (Hughes and Dornheim, 1995). These actions from the automated system occur very rapidly. The mode shifts so quickly that the pilot monitoring the system is confused and unaware of how to react to the situation. Weiner noted that some glass cockpits have clumsy automation which can create bottlenecks during high-workload periods (1989). When designing an aircraft, pilot ability to interpret the actions of the system is a vital component that must be considered for ensuring safety.

It is necessary to concentrate on the human aspect of the cockpit design. This can be achieved by examining the flying behavior of the pilots. By examining the pilot's behavior before, during and after flight, improvements can be implemented to make his/her job more comfortable and less risky. It is important to educate pilots on new automation techniques that are used within the cockpit and to emphasize the importance of utilizing the cockpit equipment properly to enhance pilot comfort. Pilots should also be instructed on how to assess both their physical and mental states prior to flying an aircraft. This will minimize the number of accidents that may occur due to fatigue and/or stress.

A.1.1.1.5. Experiment 5

The objective of the fifth experiment was to assess the degree of compatibility between expectations of the pilot (human subject) and the cockpit signals. The S-R compatibility task was a simulated version developed by Fitts and Deininger (1954). In their applications, Fitts and his associates generally required their systems to move a stylus quickly in the direction indicated by a coded visual stimulus. These studies have been generalized to various situations, which include (but are not limited to): a) Physical correspondence between paired stimulus and cognitive response (Umilte and Liotti, 1987); b) Spatial ensemble of information with multimodal cueing variables (Proctor and Reeve, 1986; Ragot, 1984); and c) Attentional processes in control of multiple tasks (Brebner, Shephard, and Cairney, 1972; Pribram and McGuinness, 1975).

The first independent variable in this study was stimulus-response signal cueing (SC). Two levels of SC were studied. These are directed cues (DC) and latent or nondirected cues (LC). Directed cues represent a set of flashing light signals in a set of presented stimuli, Latent cues are signals that just appear in the set of cueing signals. The purpose of signal cueing is to direct the subjects' attention to the occurring event. Previous studies by Proctor and Reeve (1986) and Zelaznik (1978) showed that precueing in choice-response time tasks enhances the probability of an S-R pair compatibility.

The second independent variable was the stimulus signal pairing. The number of signal pairs have been found to represent multiple tasks and also affect RT in spatial and choice S-R compatibility tasks (Hendrix, 1986; Shulman and McConkie, 1973). Here, three color signals were used: Red (R), Green (G), and Yellow (Y). The possible number of signal combinations was seven.

In our experiment, we refer to a single color as single stimulus signal, a two-color set as a two-stimulus signal, and so on. In the experiment, we have three single-stimulus signals, three two-stimulus signals, and one three-stimulus signal. The order of signal arrangement was arbitrary since in a signal set, only one color can receive a cue highlighting.

The third independent variable was whether the S-R signal compatibility was fixed or random. In a fixed S-R method, a particular response signal followed an identical stimulus signal. In this case, the subject can predict with certainty the nature of response (Hyman, 1953). On the other hand, in a random S-R method, the information pairing was generated from a Possion distribution with λ (average) of 10 seconds. In the random S-R signal pairing, the subject cannot predict the compatibility. Hence, incompatible S-R mapping was presented with uncertainty. This generated some random noise in the subject choice or response.

Two dependent variables were studied: response time and errors committed. Response time (RT) is the total time (inclusive of reaction time) to map a corresponding response color to the stimulus color. Errors were either missed opportunities to map the correct S-R color pair, or wrong response color mapping due to cue interference. Results obtained from the experiments are listed below.

(a) **Effect of S-R and Signal Presentation** - A statistical summary of averages and standard deviations of data for response times and percentage errors is shown on Table 5. The S-R cues were tested at four levels with two levels of signal presentations (random and fixed). The plots of data from Table 5 are shown in Figures 2 and 3, respectively.

Table 5. Mean and Standard Deviation of Response Time and Error Data on S-R Cues vs. Signal Presentation

S-R cue	Mean* RT(ms)		% Error	
	Random	Fixed	Random	Fixed
1	(550, 33.5)	(480, 17.5)	(24, 7.3)	(10, 1.88)
2	(730, 50.51)	(670, 60.01)	(21, 5.4)	(15, 4.2)
3	(740, 40.8)	(690, 55.3)	(30, 12.22)	(18, 7.3)
4	(510, 28.3)	(430, 19.5)	(27, 17.5)	(16, 3.6)

*(mean, std)

S-R cue: 1 = DC + DC 2 = DC + LC
3 = LC + DC 4 = LC + LC

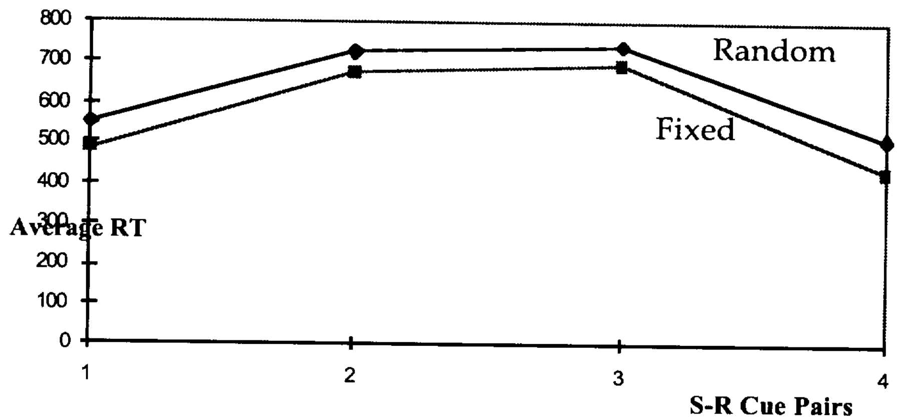

Figure 2. Mean Distribution of RT for S-R Cue Pairing Different Signal Presentations

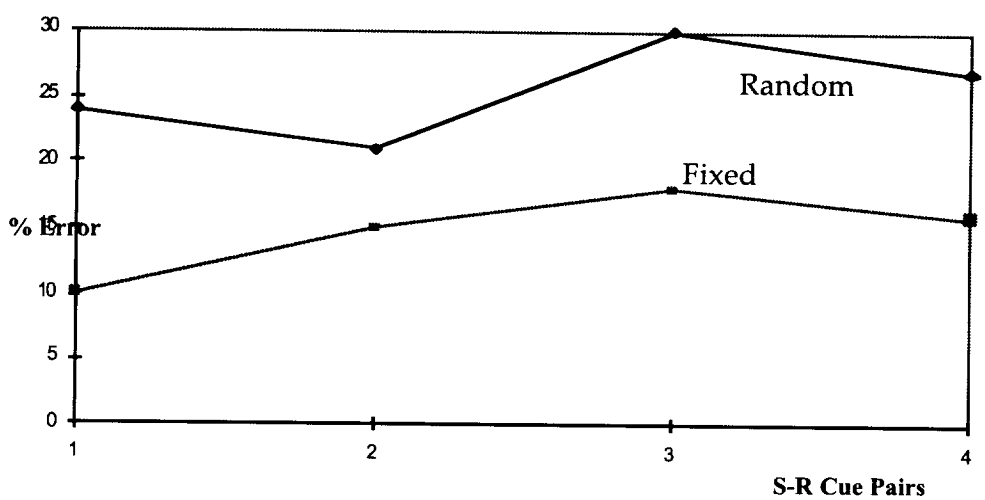

Figure 3. Mean % Error for S-R Cue Pairing at Different Signal Presentations

A statistical test of independence between signal presentation and S-R cue pairing response time was done using the Chi-Square (X^2) distribution. Since $X^2_{(calculated)} = 18.725 > X^2_{0.95} = 7.81$, we reject the hypothesis that S-R cue combinations are independent of the stimulus signal presentation (fixed or random).

(b) **Effects of Signal Pairing and Signal Presentation** - In this analysis, signal pairing consisted of: (a) a single signal, (b) a two-signal pair, and (c) a three- signal combination. There were 3 two-signal pairs with their results summarized into a single two-signal pair, and the same summarizing was done for the three single signals. This was done since the serial position of the signals were irrelevant in the analysis. Table 6 shows the mean and standard deviation values for RT and error.

Table 6. Mean and standard deviation of stimulus signal pairing vs. Signal presentation

Stimulus Signals	Mean* RT(ms)		% Error	
	Random	Fixed	Random	Fixed
A	(600, 80.9)	(520, 40.6)	(14, 2.6)	(7, 2.1)
B	(695, 64)	(625, 71.3)	(18, 4.7)	(10, 1.6)
C	(1010, 121.5)	(720, 49.6)	(20.5, 8.3)	(12, 4.5)

A = Single Signal
B = Two-Signal pair
C = Three-Signal combination

* (mean, Std.)

As shown in Figure 4 and 5, differences in mean RT and error values become more significant as the elements of signal pairs increases. This phenomenon can be attributed to non-correspondence or irrelevant information effect (Simon, 1990) caused by the signal pairing.

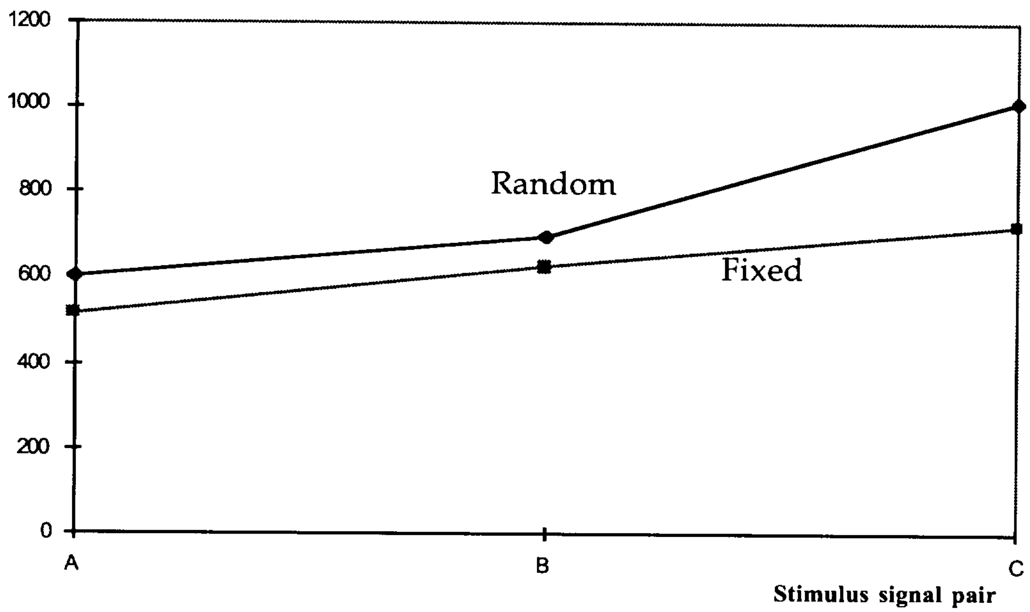

Figure 4. Mean RT For Signal Pairing Observed at Two Levels of Signal Presentation

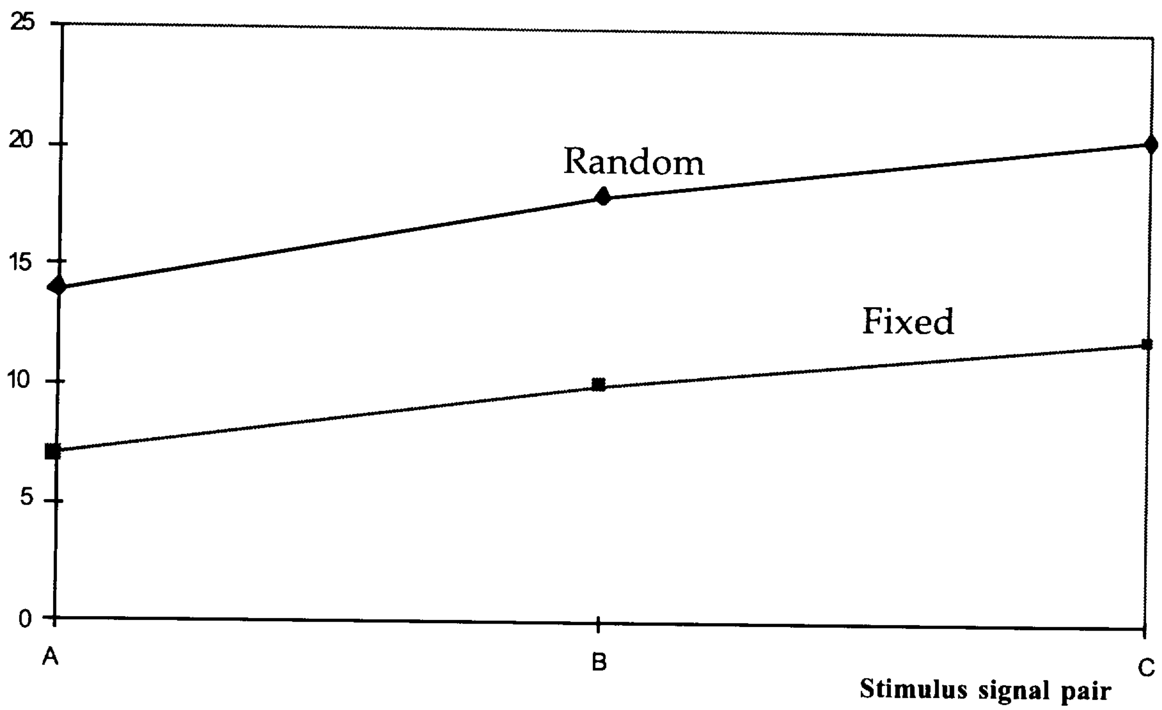

Figure 5. Mean Percentage Error for Signal Pairing Observed at Two Levels of Signal Presentation

(c) Effects of S-R cue and Signal Pairing - Table 7 shows the means and standard deviations of RT and percentage errors observed between S-R cue and signal pairing.

Table 7. Mean and standard deviation of S-R Cue Pairing vs. Stimulus Signal Pairs

S-R code	Mean * RT (ms)			% error		
	A	B	C	A	B	C
1	(480, 16.3)	(520, 31.5)	(605, 40.55)	(5, 1.2)	(7, 3.6)	(13, 4.5)
2	(501, 70.5)	(510, 18.7)	(510, 60.8)	(3, 1.9)	(7.11, 2.8)	(16, 4.9)
3	(550, 41.4)	(570, 50.3)	(620, 28.4)	(6.8, 3.1)	(1, 0)	(16, 2.8)
4	(435, 35.7)	(410, 31.0)	(533, 19.2)	(8.4, 1.33)	(18, 5.6)	(14, 1.4)

* (mean, std)

Analysis of variance (ANOVA) was used to analyze the data. The S-R cue was blocked and the stimulus signal used as the treatment. For the treatment effect $F_{(0.05,\ 2.6)} = 10.92 < F_{(calculated)} = 17.44$. This result was significant at $p = 0.036$. Hence, it can be concluded that the stimulus signal pairs have an effect on S-R cue response times.

In summary, the S-R experiments reveal the following about the effects of S-R compatibility in mental handling tasks.

(a) S-R cue combinations are dependent on the stimulus signal presentation (fixed vs. random).

(b) Mean RT and errors significantly differ by the stimulus signal presentation (fixed vs. random).

(c) Pairing of signals is an independent process from the order of signal presentation. That is, the incompatibility of signal presentation and signal grouping affect RT and errors.

(d) As the elements of signal pairing increase, there is a tendency for subjects to generate the same mean RT and errors.

(e) An analysis of variance shows that stimulus signal pairs have effect on S-R cue reaction times.

(f) The distribution of errors is higher in pursuit tracking tasks than for compensatory tracking tasks respectively.

A.1.1.1.6. Experiment 6

\This experiment was concerned with determining workload of the pilot in motion-induced orientation tasks. Compensatory and pursuit tracking tasks were used in the experiments. Workload models were derived based on extensive experiments on the AFSP using 68 subjects over a period of two and a half years. The workload model utilized the Cooper-Harper (1969) rating scale developed at NASA-Ames. The following performance metrics were derived as functions of workload index.

Case 1:

$$P = \begin{cases} e^{-WL} + \left(0.002^{1/x}\right) & , \quad 0 < WL \leq 0.28 \\ & \quad\;\; 1 \leq X \leq 4 \\ 0 & , \quad else \end{cases}$$

A model fit correlation of $R^2 = 0.718$ for a significance level of $p = 0.001$ was obtained for the best fit of P.

Case 2:

$$P = \begin{cases} Cos(WL) - 0.0336\sqrt{x} & , \quad .28 < WL \leq 0.639 \\ & \quad\;\; 4 < X \leq 7 \\ 0 & , \quad else \end{cases}$$

A model fit correlation of $R^2 = 0.931$ with $p = 0.056$ was obtained.

Case 3:

$$P = \begin{cases} e^{-WL} + 0.00172X & , \quad WL > 0.639 \\ & \quad\;\; 7 < X \leq 10 \\ 0 & , \quad else \end{cases}$$

A model fit of $R^2 = 0.613$ with $p = 0.033$ was obtained.

Since the Cooper - Harper rating scale is fuzzy, our model analysis also resulted in a fuzzy workload metric for tracking tasks (or generally, tasks utilizing the Cooper - Harper index) as

$$
\mu_{WL}(v) = \begin{cases} \dfrac{1}{1+\exp\left\{\dfrac{-\Pi v}{\sqrt{1-v^2}}\right\}} & , \quad 0 \le v \le 1 \\ 0 & , \quad else \end{cases}
$$

where v is the workload factor derived quantitatively from signal-to-noise ratio; the denominator is the peak of the step response of the closed-loop control system.

B. SUMMARY OF TECHNICAL RESULTS

B.1 Model of Human Performance In Control Tasks

Tightly controlled laboratory experiments were used for results obtained here. The following assumptions are used in deriving the models.

1. The proprioceptive delay time is very small and thus, can be considered a component of response time.
2. The human response time is proportional to the signal bandwidth.
3. Visual and aural fixation times are small and are considered a component of neuromuscular delay time (Metz, 1982).
4. The neuromuscular delay time function can be approximated by an exponential distribution with constant lag (Kleinman, et al, 1971).
5. Studies by McRuer (1974) have shown that the human describing characteristics function can be described by

$$
G_H(s) = \left(\frac{K_H e^{-ts}}{1+t_n s}\right)\left(\frac{1+T_1 s}{1+T_2 s}\right) \tag{1}
$$

where $G_H(s)$ is the human describing function. What follows in this report is an extrapolation of human control studies to an environment in which both the system and the human operator are subjected to changes in task dynamicity and difficulty. These parameters can be experimentally controlled by, say, the human postural position or simulated by control of the task damping coefficient.

B.1.2. Augmented Model for Combined Discrete and Continuous Tasks Under Variable Feedback and Task Dynamicity

This augmented model is shown in Fig. 6. The variable feedback function K_4 has the task difficulty and error correction gain K_3 as its parameters. Thus, K_4 is a weighted function defined by K_3/b. Similarly, the plant dynamics is defined by K_2/s with possible variations in either velocity or acceleration control.

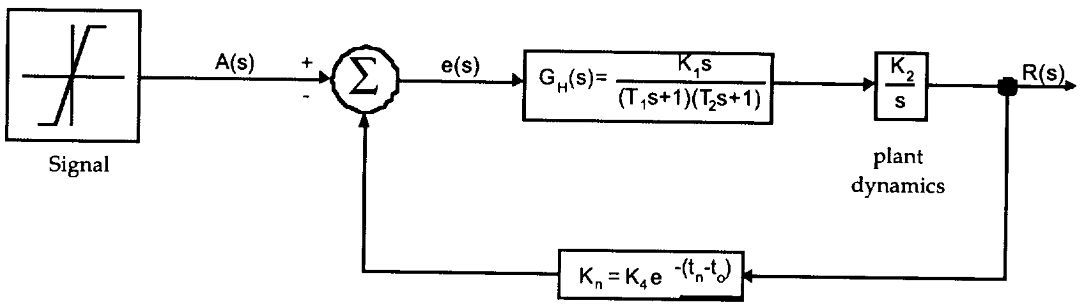

Figure 6: An Optimal Control Model of the Human Operator with Task Dynamicity

To model the situation, assume the data as given in Metz (1982) and Kleinman (1971):

$$T_1 = T_2 = 0.1\,\text{sec},\ 1.2 \le K_1 \le 2.5$$

$$0 < t_n \le 0.2\,\text{sec},\ 0.15 \le t_0 \le 0.3,\ K_2 = 1$$

$$C(s) = \frac{R(s)}{A(s)} = \frac{G_H(s)}{1 + G_H(s)K_n} \tag{2}$$

$$C(s) = \frac{K_1}{0.01s^2 + 0.2s + 1 + K_1 K_n} = \frac{100K_1}{s^2 + 20s + 100(1 + K_1 K_n)} \tag{3}$$

Substituting the appropriate values:

$$C(s) = [\frac{100(1 + \frac{K_1 K_3}{be^{t_n - t_0}})}{s^2 + 20s + 100(1 + \frac{K_1 K_3}{be^{t_n - t_0}})}](\frac{bK_1 e^{t_n - t_0}}{be^{t_n - t_0} + K_1 K_3}) \tag{4}$$

Equation (4) is a closed loop transfer function with a unit feedback. Thus,

$$G(s) = [\frac{100(1 + \frac{K_1 K_3}{be^{t_n - t_0}})}{s^2 + 20s}](\frac{bK_1 e^{t_n - t_0}}{be^{t_n - t_0} + K_1 K_3}) \tag{5}$$

Equation (5) gives the open loop transfer function required to convert the output of the closed loop to the feedback function.

B.1.3. Frequency Domain Human Response Model

Under the sinusoidal steady state, s=jw; then, equation (5) becomes

$$G(jw) = [\frac{100(1 + \frac{K_1 K_3}{be^{t_n - t_0}})}{(jw)^2 + 20(jw)}](\frac{bK_1 e^{t_n - t_0}}{be^{t_n - t_0} + K_1 K_3}) \tag{6}$$

with the following parameters: Phase margin, $\gamma = 180^o + \angle G(j\omega_c) = \arctan\frac{2\xi\omega_n}{\omega_c}$ (7)

where $$\frac{\omega_c}{\omega_n} = (\sqrt{4\xi^2+1} - 2\xi^2)^{1/2} \tag{8}$$

so $$\gamma = \arctan[2\xi(\frac{1}{\sqrt{4\xi^2+1}-2\xi^2})^{1/2}] \tag{9}$$

ξ is the damping ratio which determines the shape of C(s). By properly choosing ξ, K_3, t_n, and t_0, Ntuen and Fang (1994) have shown that for $0.3 \le b \le 0.9$, the results in Fig. 6 can be obtained.

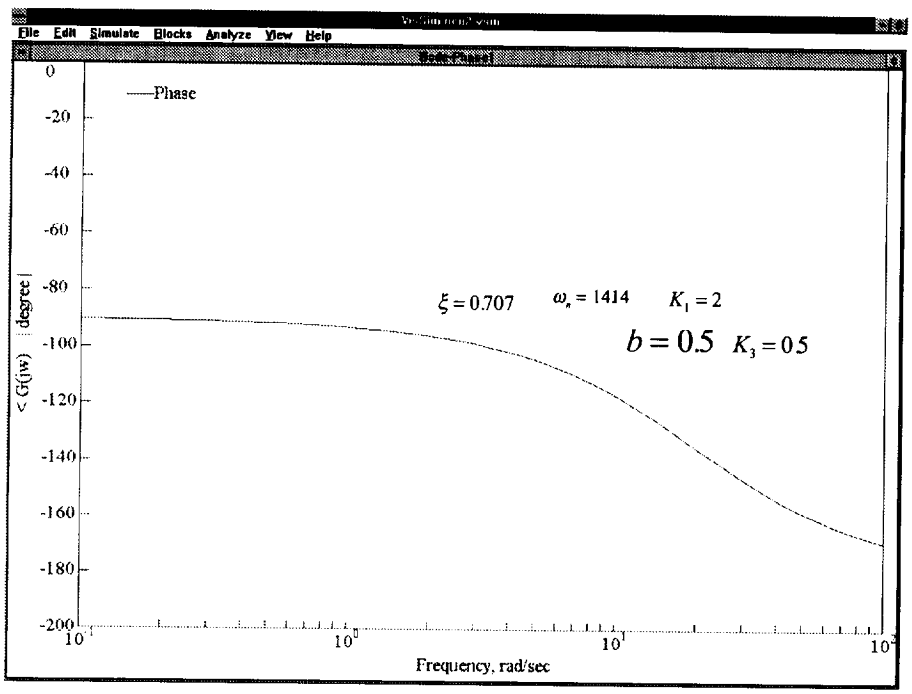

Figure 7: Frequency Response (Phase) for Augmented Human Control Model for Equation 5

From Figs. 7 and 8, the phase margin is 66° with damping ratio (ξ) of 0.707, which is suitable for a system stability range of (45° < phase margin < 70°). The gain cross-over frequency, ω_c, is 9.625. The slope of magnitude curve at 0 dB is -20 dB/decade, which means the system is stable.

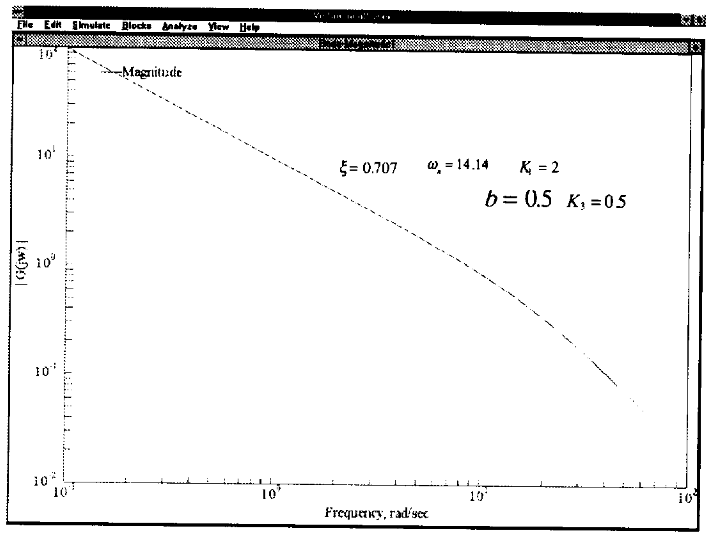

Figure 8: Frequency Response (Magnitude) for Augmented Human Control Model

B.1.4. Time Domain Human Response Model

Here, we are interested in the human response time related to the input signal. The time domain equivalent of equation (2) is:

$$R(s) = A(s)\frac{G_H(s)}{1+G_H(s)K_n} \tag{10}$$

$$R(s) = \left[\frac{100\left(1+\frac{K_1K_3}{be^{t_n-t_0}}\right)}{s^3+20s^2+100\left(1+\frac{K_1K_3}{be^{t_n-t_0}}\right)s}\right]\left(\frac{bK_1e^{t_n-t_0}}{be^{t_n-t_0}+K_1K_3}\right) \tag{11}$$

In the time domain, we derive the output function R(t) from the above equation:

$$R(t) = \frac{bK_1e^{\tau_n-\tau}}{be^{\tau_n-\tau}+K_1K_3}\left[1-\frac{1}{\sqrt{1-\xi^2}}e^{-\xi\omega_n t}\sin(w_d t+\beta)\right] \tag{12}$$

$$\text{where } 2\xi\omega_n = 20,\quad \omega_n^2 = 100\left(1+\frac{K_1K_3}{be^{\tau_n-\tau}}\right),\quad \omega_d = \omega_n\sqrt{1-\xi^2},\quad \beta = arctg\,\sqrt{1-\xi^2}\Big/\xi \tag{13}$$

Similarly, we have velocity response V(t) and acceleration response Z(t) as follows:

$$V(t) = \frac{dR(t)}{dt} = K_n a e^{-at}\sin(\omega_d t+\beta) - K_n\omega_d e^{-at}\cos(\omega_d t+\beta) \tag{14}$$

$$Z(t) = \frac{dV(t)}{dt} = (\omega_d^{\,2} - a^2)K_n e^{-at}\sin(\omega_d t + \beta) + 2K_n a\omega_d e^{-at}\cos(w_d t + \beta) \tag{15}$$

where
$$K_n = \frac{bK_1 e^{\tau_n - \tau}}{(be^{\tau_n - \tau} + K_1 K_3)\sqrt{1-\xi^2}} \qquad a = -\xi\omega_n \tag{16}$$

The optimal results from experiments using the above results are shown in Tables 3 and 4. (Section A.1)

The plot of R(t) against time (t) for different values of ξ is shown in Fig. 9. As the damping ratio (ξ) increases from 0.65 to 0.86, the maximum overshoot of reaction slows down. The delay time and rise time are also getting smaller. The transient response and stable response of the system can be guaranteed. The stable response occurs between 0.4 and 0.5 seconds. As the damping ratio decreases, the system experiences a steep overshoot. The signal reaction time by the controller is $0.4 \pm 0.85\sigma$, $0 \le \sigma \le 0.3$, where σ is the standard deviation.

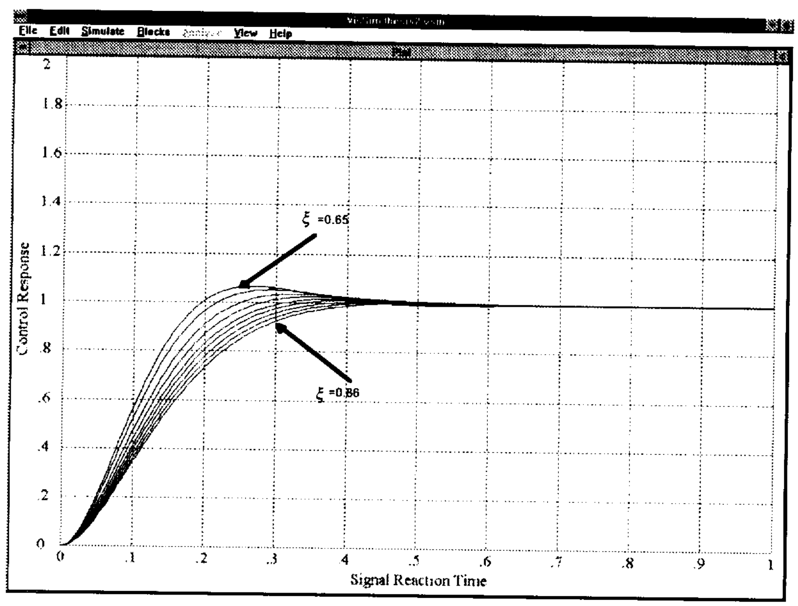

Figure 9: Time Domain Response for Augmented Human Control Model

Figure 10 shows the velocity response curve. The shape of the curve is determined solely by the damping ratio (ξ). As shown in Figure 10, a time response which is equivalent to a gain-crossover frequency exists. This value is $\omega_c = 5.4Hz$, and takes place regardless of the value of ξ, such that $0.65 \le \xi \le 0.86$. The effective time delay occurs at the frequency of 0.182 sec. The velocity signal response time is $0.6 \pm 0.1\sigma$, $1 \le \sigma \le 1.5$, where σ is the standard deviation.

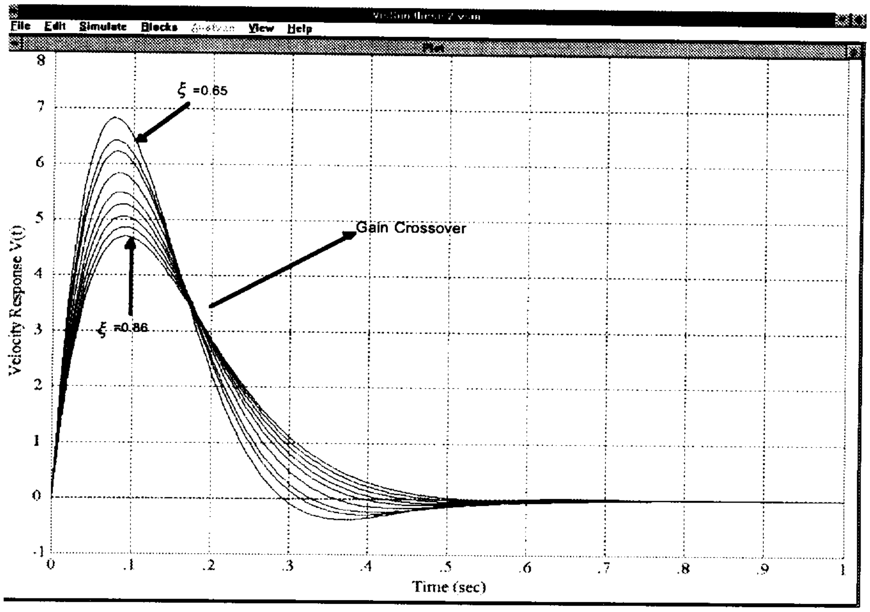

Figure 10: Velocity Response for Augmented Human Control Model

In Fig. 11, the acceleration response is presented. The asymptotic gain crossover frequencies are ω_1 and ω_2 at points A and B, respectively. The corresponding values are 20Hz and 3.52Hz. The maximum time delay between the crossover points is denoted by $T_d = \max\ (1/\omega_1, 1/\omega_2)$. The derivation of T_d is given by Biernson (1988). From Fig. 10, $T_d = \max\ (0.05, 0.284) = 0.284\,\text{sec}$. The acceleration response time is $0.5 \pm 0.12\sigma$, $0.958 \leq \sigma \leq 1.25$, where σ is the standard deviation.

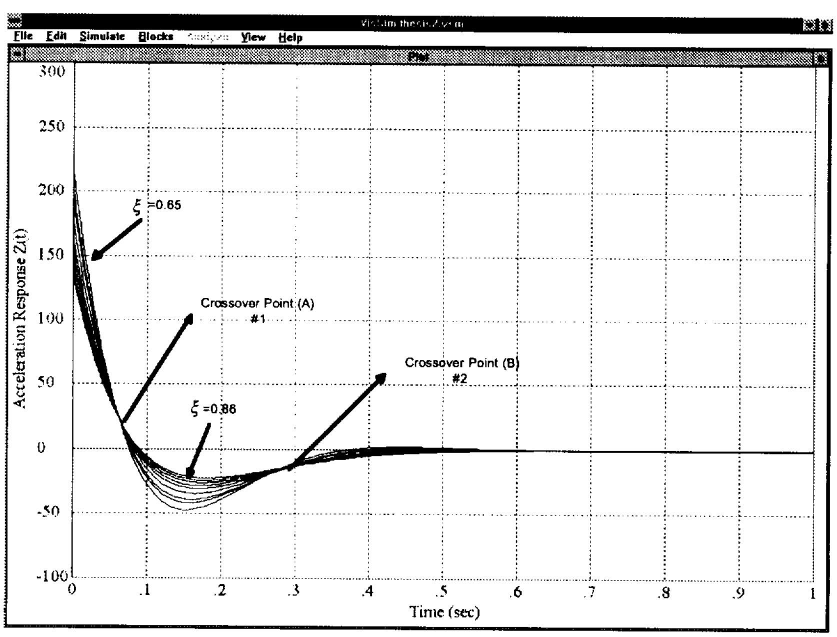

Figure 11. Acceleration Response for Augmented Human Control Model

B.1.5. Human Response Error Function

The error closed loop transfer function derived is:

$$G_e(s)=\frac{1}{1+G_F(s)G_H(s)}=\frac{s^2+20s+100}{s^2+20s+100(1+K_1K_n)}=\frac{s^2+20s+100}{s^2+20s+100(1+\frac{K_1K_3}{be^{\tau_n-\tau}})} \qquad (17)$$

The steady state error of the system is about 0.65. The same result can be validated mathematically by the following equation:

$$e_{ss}=\lim_{s\to 0} s*G_e(s)*A(s)=\lim_{s\to 0}\left\{s*\left[\frac{s^2+20s+100}{s^2+20s+100(1+\frac{K_1K_3}{be^{\tau_n-\tau}})}\right]*\frac{1}{s}\right\}=0.639$$

where, $b=5.5$, $K_3=2$, $K_1=1.56$, $\omega_n=125$, $\xi=0.8$, $\tau_n=\tau=0.2$.

B.1.6. Model Analysis and Results

All the models derived were analyzed using the VISIM/ANALYZE™ software (VISIM, 1983). Our laboratory experiments show a minimum velocity time gain occurs at about 400ms while the acceleration time gain occurs at 150ms. The simulation experiment showed that in the interval $1.2 \le K_1 \le 2.5$, the compensatory time required lies between 0.65s and 0.9s respectively. A compensatory gain time of 0.65s corresponds to a gain crossover frequency (ω_c) value of 10.47 rad/sec, with a corresponding phase angle of 63° (Young et al., 1964). When the compensatory gain time is 0.955, ω_c is 5.843 rad/sec at an angle of 74°. In order to achieve a satisfactory human transient response for a high gain system, a phase angle margin of 40° - 70°, equivalent to compensatory gain times of 0.65 - 0.80, should be achieved. Table 8 shows sample simulated results.

Table 8: Sample Control Parameters For Flight Simulator Design

Compensatory gain time (s)	Crossover frequency rad/sec	Phase angle
0.65	10.47	63°
0.68	9.625	65°
0.707	8.847	66°
0.72	8.669	66.3°
0.75	7.968	68°
0.78	7.524	68.9°
0.8	7.177	69.6°

B.2. Human Performance Model For A Closed-Loop Supervisory Control Task

The model is derived based on laboratory experiments performed with human subjects on the AFSP. The human subjects were engaged in a closed-loop supervisory control with or without random postural orientation (sudden changes or jerks on the initial sitting position). Figure 12 is used to illustrate the model concept.

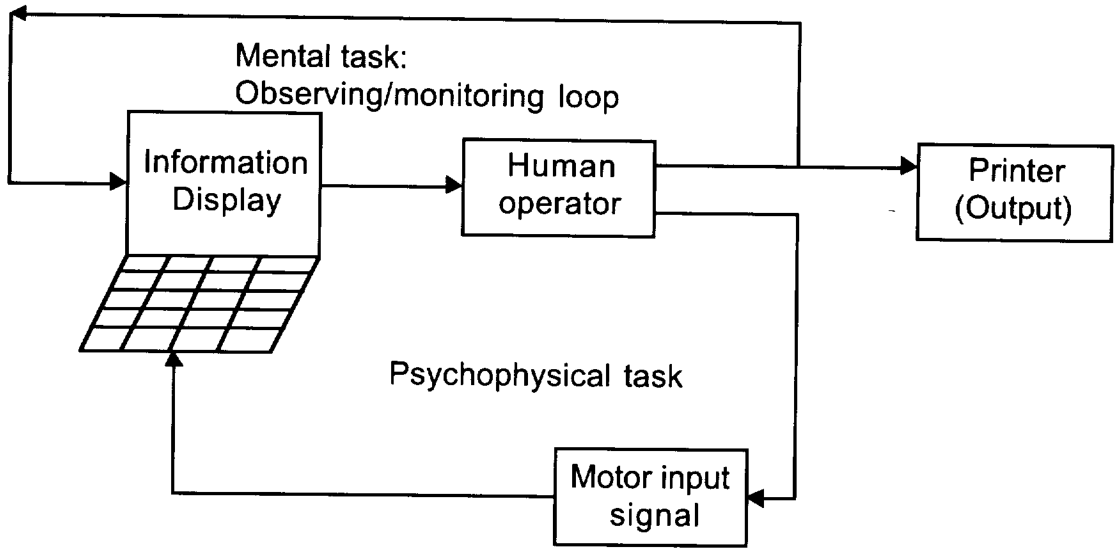

Figure 12: A closed loop task with the human operator

Not only are the visual and proprioceptive cues required by the human operators in these tasks, vestibular and kinesthetic cues are also involved from sensors in the eyes, ears, and the skin. The nature of the optimal control model (OCM) shown in Fig. 12 allows the application of a generalized human operator describing function developed by McRuer (1974) as given in Eq. (1). For demonstration, we investigated compensatory tasks. The model in Fig. 13 can be expanded to include the rate loop as shown:

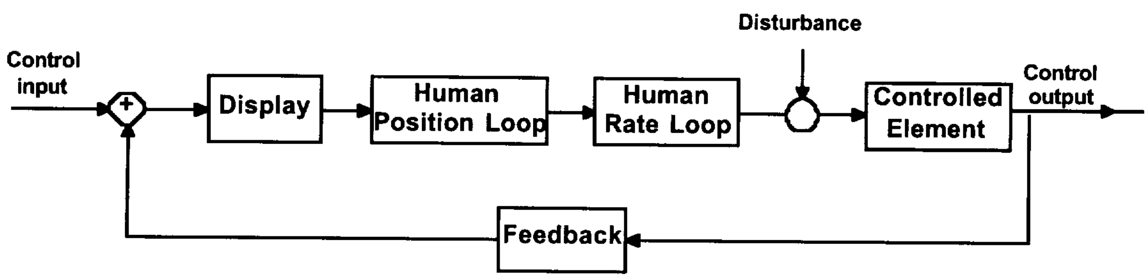

Figure 13: Human Performance Model Compensatory Tracking Task

In Fig. 13, the controlled element is the computer. The describing functions are:

Human position loop: $$\frac{K_H(T_L s+1)}{(T_I s+1)} \tag{18}$$

Human rate loop: $$\frac{e^{-\tau s}}{(T_N s+1)} \tag{19}$$

Controlled element: $$\frac{K_c}{s(s+1)(s-\tau)} \tag{20}$$

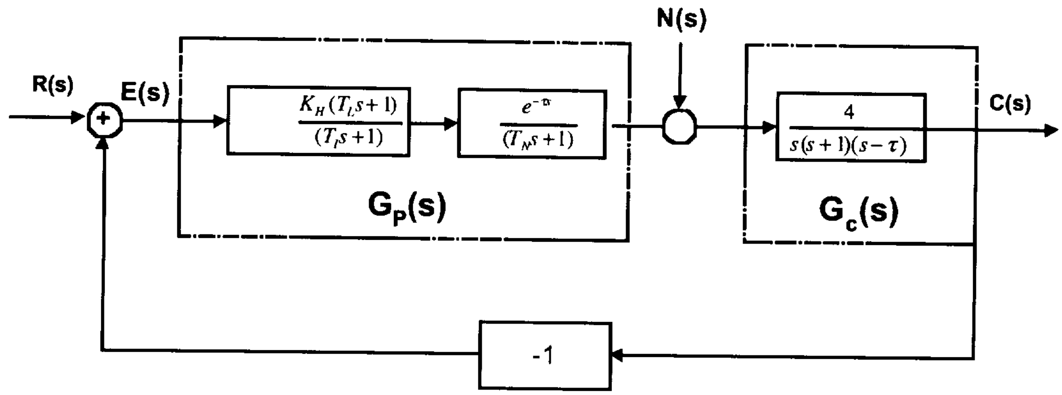

Figure 14: Control Model for Close-Loop in Compensatory Task given in Fig.13.

When considering the noise input, we have:

$$C(s)=\frac{G_P(s)G_C(s)}{1+G_P(s)G_C(s)}R(s)+\frac{G_P(s)}{1+G_P(s)G_C(s)}N(s) \tag{21}$$

$$E(s)=\frac{1}{1+G_P(s)G_C(s)}R(s)-\frac{G_P(s)}{1+G_P(s)G_C(s)}N(s) \tag{22}$$

The open loop transfer function for the system input only is $G_0(s)=G_P(s)G_C(s)$ (23)

By using some results obtained in Section B.1.2: T_I=0.35, T_L=0.25, K_H=5.5, τ =0.19 (24)

Therefore, the human describing function proposed in its simplest form is:

$$G_P(s)=\frac{K_H(T_L s+1)e^{-\tau s}}{1+T_I s}=5.5e^{-\tau s}\frac{(0.25s+1)}{(0.35s+1)} \tag{25}$$

Using *Pade* approximation, the pure time delay above can be presented as:

$$e^{-\tau s}=\frac{1-\tau s/2}{1+\tau s/2}=-\frac{\tau s/2-1}{\tau s/2+1} \tag{26}$$

So the open loop transfer function for system input is:

$$G_0(s)=-\frac{K_H(T_L s+1)}{1+T_I s}\cdot\frac{K_c}{s(s+1)(s-\frac{2}{\tau})}\cdot\frac{\tau s/2-1}{\tau s/2+1}=-\frac{K_H(T_L s+1)}{1+T_I s}\cdot\frac{K_c}{s(s+1)}\cdot\frac{1}{\tau s/2+1} \tag{27}$$

The closed loop transfer function is:

$$G_c(s) = \frac{G_o(s)}{1+G_o(s)} = \frac{5.5s+22}{0.35s^4+8.35s^3+28s^2+25.5s+22} \tag{28}$$

B.3. Mean Value Human Response Model for The Aggie Flight Simulator Platform (AFSP)

In this section, theoretical models describing the human operator response functions in the AFSP environment are described. The models are relaxed mean value derivations of the existing characteristic functions that utilize response and neuromuscular time parameters.

B.3.1. Basic Assumptions

The four basic assumptions from section C.1. are still valid here as is the following assumption. The human operator is involved in a supervisory (prediction) task by anticipating event arrival times and responding to times required to initiate event execution.

B.3.2. Model Development

By using the weighted response times and muscular (movement) times against their respective characteristics functions, we define the following relationship:

$$\frac{T_R}{K_P} = \alpha \frac{T_M}{K_H} \tag{29}$$

where α is an amplification factor that relates the task reaction time to stimuli response time. From Eq. (24):

$$T_M = \frac{K_H}{\alpha K_P} T_R \tag{30}$$

Let $$\left| g = (\alpha)\frac{K_H}{K_P} \right. \tag{31}$$

By various experimental results (see, e.g., Vinge and Pitkim, 1972), it is well known that T_M is proportional to T_R with "g," the constant of proportionality.

Hence, from Eq. (26):

for g > 0, that is : $$g = \frac{K_H}{K_P} > 0 \tag{32}$$

We can rewrite Eq. (32) as $$0 < g\frac{K_P}{K_H} < \infty \tag{33}$$

AFSP As A First Order Plant

For first order plants, Hess (1988) has shown that:

$$K_P = C_p e^{-\tau s} \tag{34}$$

and by a general assumption, K_H is: $K_H = e^{-\tau_n s}$ (35)

thus from Eq. (30): $$T_M = \frac{(\alpha)e^{-\tau_n s}}{C_P e^{-\tau s}} T_R \quad (36)$$

$$T_M = \frac{\alpha e^{(-\tau_n s)}}{C_P} T_R \quad (37)$$

$$T_M = \lambda(s)\, T_R \quad (38)$$

where $$\lambda(s) = \frac{\alpha e^{-(\tau_n - \tau)s}}{C_P} \quad (39)$$

Note that Eq. (38) is a Laplace function of the parameter s. Thus, we can determine the first moment of the transform using the general Laplace equation: $M_n = \frac{1}{(-1)^n} \frac{d^n}{ds^n} L(s)\Big|_{s=0}$

That is $$\lambda(0) = \frac{-\alpha(\tau_n - \tau)}{C_P} \quad (40)$$

The mean value prediction function can then be written as $T_M = \lambda(0) T_R = \frac{-\alpha(\tau_n - \tau)}{C_P} T_R$, (41)

provided: $$\frac{-\alpha(\tau_n - \tau)}{C_P} > \theta,\ where\ \theta > 0$$

or: $$\tau > \tau_n + \theta \frac{C_P}{\alpha} \quad (42)$$

AFSP As A Second Order Plant

For the second order plant, Hess (1980) has shown that: $K_P = C_P(Bs + 1)e^{-\tau s}$ (43)

Therefore: $$T_M = \frac{\alpha e^{-\tau_n s}}{C_P(Bs+1)e^{-\tau s}} T_R \quad (44)$$

$$T_M = \frac{\alpha T_R}{C_P(Bs+1)} e^{-(\tau_n - \tau)s} \quad (45)$$

Let $$\lambda(s) = \frac{\alpha e^{-(\tau_n \tau d)}}{C_P(Bs+1)} \quad (46)$$

$$\frac{d\lambda(s)}{ds}\bigg|_{s=0} = \frac{C_P(Bs+1)(-\alpha)(\tau_n - \tau)e^{-(\tau_n,\tau)s} - C_P B\alpha e^{-(\tau_n-\tau)s}}{C^2{}_P(Bs+1)^2}\bigg|_{s=0}$$

thus: $$T_M = \lambda(0)T_R = \frac{-\alpha(\tau_n - \tau + B)}{C_P}R_R \tag{47}$$

provided: $$\frac{-\alpha(\tau_n - \tau + B)}{C_P} > \theta, \quad where\ \theta > 0$$

That is: $$\tau > \tau_n + B + \theta\frac{C_P}{\alpha} \tag{48}$$

B.4. Quantitative Workload Modeling and Mental Task Handling Quality

B.4.1. Preamble

As the aircraft cockpit becomes more automation dependent, the human pilot is more often engaged in mental task handling. Among these tasks are system state predictions, anticipation of event occurrences and mental simulation of the entire spectrum of tasks to be executed during particular phases of flight.

The concepts of workload are characterized by multifaceted definitions (Jex, 1988). These include the considerations of task characteristics, the human characteristics, and the task environment. Usually, however, workload measures are used to measure human performance. This approach has generated various opinions and models, including, but not limited to, mental workload models (Moray, 1979), and physical workload models (Strasser, 1977).

The performance of the human operator is usually a concern in human-machine systems. Thus, minimizing workload is considered an important goal in system design (Welford, 1978). For the most part, workload indicators are usually obtained through the subjective ratings of the task characteristics by the person performing the task. For example, how the human operator perceives the level of "difficulty" associated with the task; how much "effort" is required, and the level of "comfort" experienced while performing the task. All these attributes are subjective, imprecise and vague (Moray, Eisen, Money and Turksen, 1988).

B.4.2. Quantitative Workload Index (QWI)

Subjective measure of workload often requires the human operator to evaluate the task according to perceived dimensions of "difficulty". Quite often, the degree of difficulty is confused with, or used interchangeably with, degree of complexity. Task difficulty as used here is a measure of how the human operator perceives the task in terms of how "hard" or "easy" it is to perform. Task difficulty can be measured in terms of error, time and some cognitive levels of "comfort" (Watson and Ntuen, 1996).

We should note that task complexity is not necessarily the same as task difficulty. Task difficulty may or may not be a function of complexity. In the QWI model (Watson and Ntuen, 1996), both concepts are used interchangeably for reasons to be explained later.
The QWI is defined by

$$QWI = \begin{cases} \dfrac{c - e^{-0.5a}}{c + e^{-a}} & , \ \textit{for stable systems} \\ & \ \ (\textit{no oscillatons}) \\ \dfrac{c - (a/b)e^{-a}}{c + e^{-a}} & , \ \textit{for unstable systems} \end{cases} \tag{49}$$

where **c** is a hypothetical work content or "load" (this may be a distribution of time available to complete a task); e^{-a} is energy loss to the work environment (see Gheorghe, 1979); $c + e^{-a}$ is the total system work content; and **a** is the complexity parameter. The complexity for parameter **a** by can be defined in various ways. For our compensatory task experiment:

$$\mathbf{a} = \frac{RMS(e)}{RMS(s)} \tag{50}$$

where RMS(e) is the root mean square of control error and RMS(s) is the root mean square of the task dynamicity: (s-1) for position error; (s-λ) for velocity, $(s-\lambda)^2$ for acceleration; **b** is the system damping coefficient, and

$0 \le QWI \le 1$, with the conditions: $(c - e^{-0.5a}) > 0$, for $b = 0$
$c \ge (a/b)e^{-a} \ge 0$, for $b > 0$

No evaluations for b < 1 are available in the QWI model. Note that the complexity parameter **a** can be interpreted in terms of signal-to-noise ratio. The damping coefficient controls the shape of the parameter.

B.4.3. Workload Differential Model

Assume that due to design or system instability factors (noise, motion, etc.) the system complexity has increased from a_1 to a_2. The change in workload, denoted by $\Delta W(a)$ is given by

$$\Delta W(a) = \int_{a1}^{a2} QWI(a)da \tag{51}$$

By substituting Eq. (48) in Eq. (50) and simplifying the integration, we have,

$$\Delta W(a) = \begin{cases} \left(a + \ln\left(c + e^{-a}\right)\right) + 2/c^{-0.5} \arctan\left(e^{-0.5a}/c^{-0.5}\right)\Big|_{a1}^{a2}, & \textit{for } b = 0 \\ \\ \left(a + \ln\left(c + e^{-a}\right)\right) + \left(1/b \ln\left(c + e^{-a}\right)\right)\Big|_{a1}^{a2}, & \textit{for } b > 0 \end{cases} \tag{52}$$

B.4.4. A Fuzzy Model for Mental Workload Assessment

B.4.4.1. Background

Because of the subjectiveness involved in workload measures, it is difficult to determine a standard workload metric which is stable, sensitive, and global (Jex, 1988). However, recent interest, due in part to the progress in fuzzy set theory (Zadeh, 1973), has concentrated on quantifying the subjective workload measures. Our project contributions to this issue are: 1) assessing the task characteristics, and 2) deriving fuzzy workload measures in an actual experimental condition using the task characteristics. Compensatory tracking tasks at three levels of 'perceived' complexities are used as a proof-of-concept database. The compensatory tasks studied are: position tracking, rate tracking and acceleration tracking. Instability factors are introduced in each task as a measure of complexity. Fuzzy workload distributions are obtained using the workload metric developed by Watson and Ntuen (1996).

B.4.4.2. Fuzzy Theory

Zadeh (1973, 1975) introduced the theory of fuzzy set to address the issues associated with vagueness and impreciseness by hedging subjective opinions on a cognitive scale of preference. Eshrag and Mamdami (1979) developed a general approach to linguistic approximation to weight the "behavioral preference" of choice in multi-attribute decision making problems. Others, for example, Baas and Kwakernaak (1977), developed methods for ranking subjective alternatives. In general, fuzzy metrics, developed on subjective scales, are known to follow certain laws of comparative judgment (Thurstone, 1927).

The fundamental definitions of a fuzzy set theory are given as follows (Zadeh, 1973):
Let X = {x} be a set of attributes, then a fuzzy set A ∈ X is a set of ordered pairs

$$A = \{x, \mu_A(x)\}, x \in X \tag{53a}$$

where $\mu_A(x)$ is called the characteristic function or graded membership of x in A (Zadeh, 1975). The membership function $\mu_A(x)$ maps the fuzzy set A onto the interval [0, 1]; that is μ_A: A → [0, 1]. Similarly, let Y = {y} be a set of criteria variables, then a fuzzy set B ∈ Y is a set of ordered pairs

$$B = \{y, \mu_B(y)\} \quad y \in Y \tag{53b}$$

and μ_B: B → [0, 1]. Note that $\mu_A(x)$, $\mu_B(y)$ can be assumed to have a known distribution, mathematically or perceptually. The fuzzy distribution can be a real continuous phenomenon or may represent a discrete countable event. The interaction of A and B is defined by:

$$\mu_A(x) \wedge \mu_B(x) = \min\{\mu_A(x), \mu_B(x)\} \tag{54}$$

The union of A and B is defined by: $\mu_A(x) \cup \mu_B(x) = \max\{\mu_A(x), \mu_B(x)\}$ (55)

The extended maximum operator combines the definitions in Eqs. (54) and (55). This is defined by:

$$\left.\begin{array}{l}\mu_A(x)\bigcup\mu_B(x)=Sup\{\min[\mu_A(u),\mu_B(u)]\\ \left(\left(u,v/x=\max(u,v),\forall x\in\Re\right)\right)\end{array}\right\} \quad (56)$$

B.4.4.3. Theoretical Development

The interaction of the Cooper-Harper (1969) task levels can be represented in a linguistic geometric space as shown in Fig. 15; where A is for Level 1, B for Level 2, and C for Level 3, respectively. In Figure 14, the fuzzy boundary between A and B, and between B and C represent some "occluded" interaction of cognitive opinions, and can be modeled as event interactions. Specifically, let $\mu_A(x)$, $\mu_B(x)$, and $\mu_C(x)$ represent the fuzzy membership of levels A, B, and C; then the aggregate cognitive fuzzy rating is given by

$$\mu_S(x)=\mu_A(x)\bigcup\mu_C(x)-[\mu_A(x)\wedge\mu_B(x)\wedge\mu_C(x)] \quad (57)$$

where μ_B (x) is the fuzzy membership for describing the task rating on CH scale.

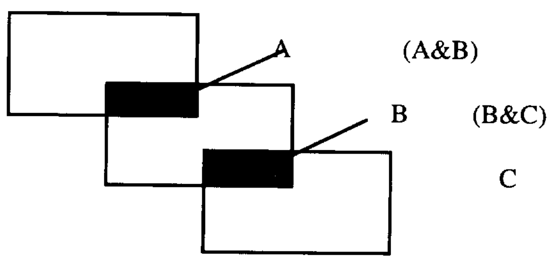

Figure 15: Set Representation of FHQ Levels with Fuzzy Boundaries

From Eq. (57), it is easy to show that

$$\begin{aligned}\mu_S(x)&=\mu_A(x)\bigcup\mu_B(x)\bigcup\mu_C(x)-\mu_B(x)[\mu_A(x)\bigcup\mu_C(x)]\\&=\mu_A(x)\bigcup\mu_B(x)\bigcup\mu_C(x)-g(x)\\g(x)&=\mu_B(x)\bigcap[\mu_A(x)\bigcup\mu_C(x)]\end{aligned} \quad (58)$$

where g(x) is a fuzzy function describing the degree of overlapping opinions. The term g(x) can be obtained by using the general overlapping function (Eshrag & Mandani, 1979).

$$\mu_{MN}(x)=\frac{\mu_M(x)\bigcup\mu_N(x)-\{\mu_M(x)+\mu_N(x)\}}{\mu_M(x)\wedge\mu_N(x)} \quad (59)$$

$$\mu_{MN}(x)\in(-1,\infty)$$

We want $\mu_{MN}(x)\in[0,1]$, hence from equation (55), the scaled overlapping function is

$$g(x)=\begin{cases} 1/2\left(\mu_{MN}(x)+1\right), & -1\le \mu_{MN}(x)<0 \\ 1-\dfrac{1}{\mu_{MN}(x)+1}, & \mu_{MN}(x)\ge 0 \end{cases} \tag{60}$$

B.4.4.4. Mapping Perceived Difficulty Into CH Scale

Let D be a space of point objects with a generic element denoted by d (D is the difficulty rating). Associated with $U_D(d)$ is $D = \{\mu_D(d_i), d_i), d_i \in \to [0, 1]; \; i=1, 2 \ldots 5\}$. Equivalently, define X such that X is $\{\mu_x(x_j), x_j), x_j \in X\} \in \to [0, 1]$ is the fuzzy description function of the CH scale; j = 1, 2,..., 10. A fuzzy relation R on the Cartesian set N x M (N = 5, M = 10) is defined as a mapping of D onto X such that $\forall\, d_i \in D, \forall\, x_i \in X, R(d_i, x_i) \in [0, 1]$. According to Yager (1977), R is a measure of the possibility or perception of how the task difficulty contributes to task handling quality. The greater the value of $R(\cdot)$, the more difficult the task handling performance. The fuzzy distribution induced by $R(\cdot)$ is defined by

$$\mu_D(d)=\max\left\{\mu_R(d,x)\wedge\mu_D(d)\right\} \tag{61}$$

B.4.4.5. Experimental Fuzzy Distribution

The experimental fuzzy distributions obtained are aggregations of subjective and objective measurements of the task workload defined in equation (48) (with c = 1). The fuzzy workload model is defined by

$$\mu_{WL}(v)=\begin{cases} \dfrac{1}{1+\exp\left\{\dfrac{-\pi v}{\sqrt{1-v^2}}\right\}}, & 0\le v\le 1 \\ 0, & else \end{cases} \tag{62}$$

where v = QWI; the denominator term is the peak of the step response of the closed-loop control system (Biernson, 1988).

B.4.4.6. Sample Results

Eight graduate students (5 males and 3 females) with an average of 24.3 years of age took part in the study under the experimental conditions specified earlier. The experiment involved trials in random order to ensure that learning effects were eliminated with the aggregation of the difficulty and CH ratings based on the obtained QWI. The membership values were calculated using Eq. (62) and the normalized values obtained by dividing each value with the maximum rating obtained. Tables 9 through 11 give sample values for position, rate, and acceleration compensatory control tasksm respectively. These data are displayed in Figure 16 by plotting the fuzzy membership as a function of QWI. Figure 16 indicates fuzzy membership distribution by task difficult levels. This is similar to the CH levels described earlier. Figure 17 shows the average CH rating for each task level as a function of system instability. Similarly, Figs. 18 and 19 show the distribution of workload for compensatory tracking tasks for complexity levels of b = 0 and 0.85, respectively.

Table 9: Workload Membership Function For Position Compensatory Task

Workload index	Calculated membership	Normalized membership
0.17	0.632	0.712
0.22	0.67	0.755
0.28	0.714	0.804
0.31	0.736	0.829
0.35	0.764	0.86
0.43	0.818	0.921
0.55	0.888	1

Table 10: Workload Membership Function For Rate Compensatory Task

Workload index	Calculated membership	Normalized membership
0.39	0.791	0.827
0.48	0.848	0.887
0.59	0.907	0.949
0.66	0.94	0.983
0.7	0.956	1

Table 11: Workload Membership Function For Acceleration Compensatory Task

Workload index	Calculated membership	Normalized membership
0.63	0.927	0.927
0.74	0.97	0.97
0.82	0.989	0.989
0.86	0.995	0.99
0.95	0.999	1

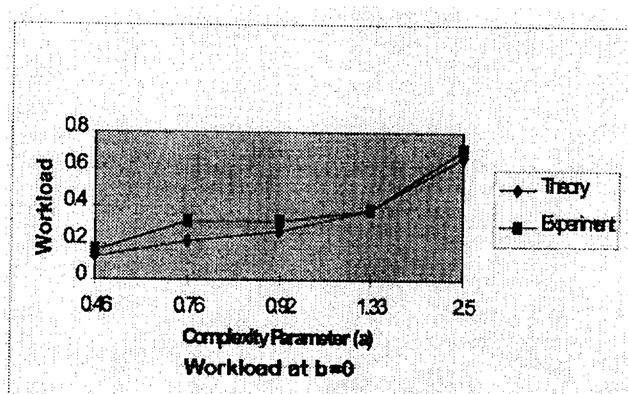

Figure 16: Fuzzy Membership Distribution by Task Levels

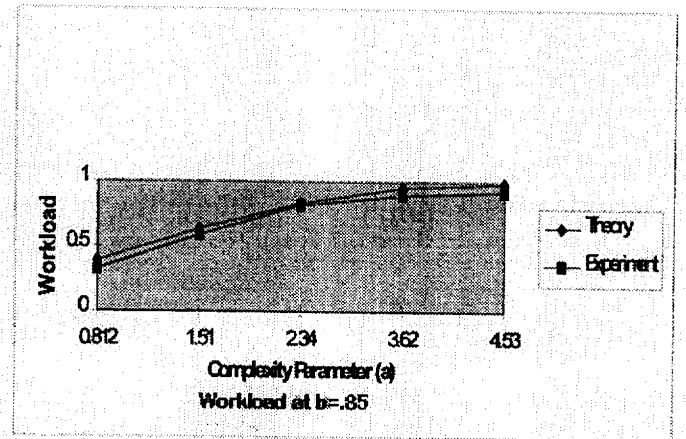

Figure 17: Average CH Rating for each Task Level as a Function of System Instability

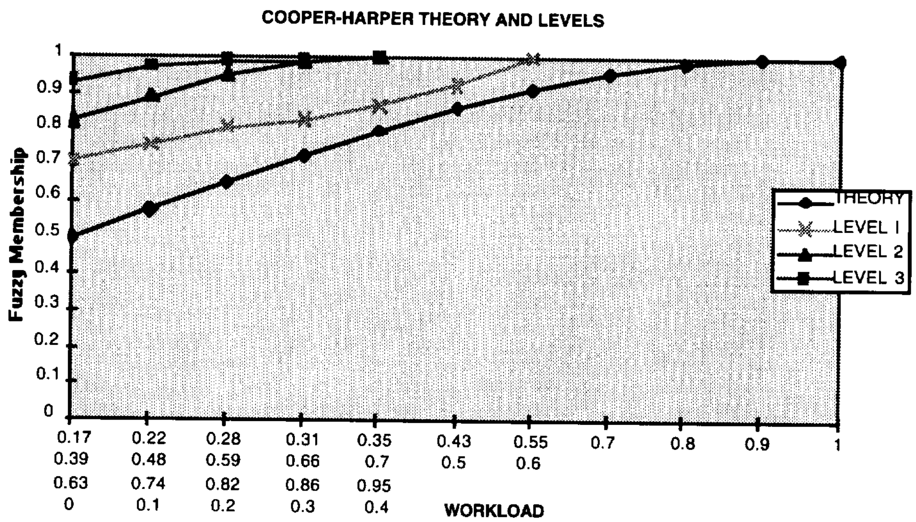

Figure 18: Fuzzy Membership Distribution By Task Levels.

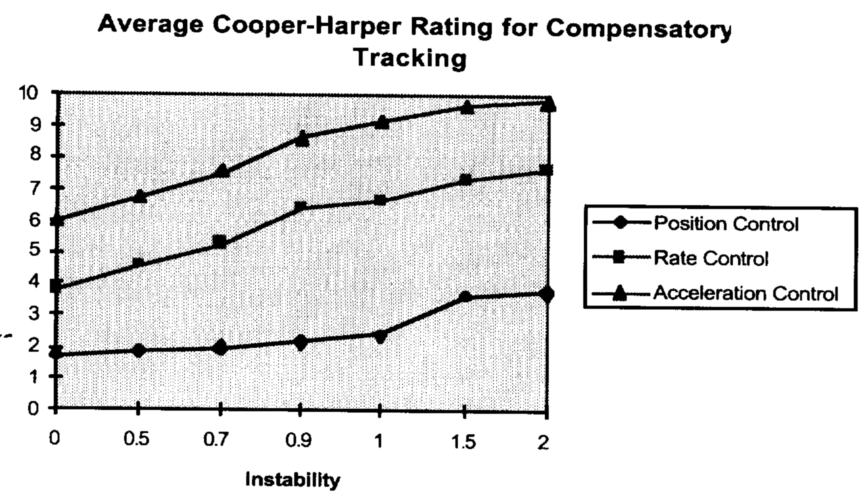

Figure 19: Average CH Rating for each Task Level as a Function of System Instability.

C. AREA PROGRAM ACTIVITIES

C.1. Education Efforts

(a) During the project period, 4 African-American students completed their graduate degrees in Industrial Engineering and 1 in electrical engineering; 5 graduate students supported by NASA-CORE took job internships with companies; 4 graduate students are currently enrolled in a graduate program in industrial engineering; and six undergraduate students were supported and mentored, of which three entered a graduate program.

(b) Through the NASA-CORE grant, the Human-Machine Systems Engineering (HMSE) Laboratory was further developed technically. The number of both undergraduate and graduate students choosing the HMSE option also doubled. The interest created a new option track at the graduate program and is a header in a proposed Ph.D program plan submitted to the state of North Carolina. Through leverage with the Army Research Laboratory grant of $1.6 million, an Institute of Human-Machine Studies has been authorized for operation. The NASA-CORE grant also supports a yearly Symposium on Human Interaction with Complex Systems, which started in 1995. North Carolina A&T State University is now regarded as one of the few universities with a research strength in Human-Machine Systems Engineering.

(c) Through the NASA-CORE grant, we also operated a yearly Summer Para Researcher Program in Human-Machine Systems Engineering for high school students. The cost sharing has been through yearly grants from the Office of Naval Research and the Army Research Office, respectively. In the past three years of the program life cycle, a total of 115 students have attended. Based on responses to our questionnaire for program alumni, 47% have entered college and majored in engineering, 11% entered community colleges, 15% sought trade as independent craftsmen, and the rest entered college in non-engineering majors. The Department of Industrial Engineering has recruited a significant number of high school students through this program.

C.1.1. Student Theses and Projects

1. Winchester, W. E. (1994). Human Response Time In Dynamic Orientation Task Environment and Its Effect on Flight Handling Quality (MSIE Thesis).
2. Smith, D. S. (1995). Human Response Errors in Motion Induced Tasks (MSIE Thesis).
3. Jihong, F. (1997). Performance Models of the Human Operator In Discrete and Continuous Tasks (MSIE, Thesis: Work Performed for NASA-CORE Under Leverage Grant from Office of Naval Research).
4. Watson, A. R. (1996). Effects of Induced Motion Changes During Task Performance on Pilot Workload (MSIE Thesis).
5. Pitman, M. S. The Effect of Prolonged Sitting on Mental Task Performance (MSIE Thesis in progress).
6. Strickland, D. The Effect of Personality on Supervisory Control (MSIE Thesis in progress).
7. Bellman, T. The Effect of Personality on Use of Situation Awareness Aids. (MSIE Thesis in progress).

C.1.2 Educational Outreach and Seminars

The following seminar presentations were organized:

1. Symposium on Human Interaction With Complex Systems, Four Seasons, Greensboro, NC, September 18-20, 1994 (Dr. Celestine Ntuen, General Chair, Drs. E. H. Park and J. H. Kim, Program Chairmen). 133 participants were in attendance and 42 technical papers presented; this resulted in 419 pages of conference proceedings.

2. Flight Handling Quality and Pilot-Vehicle Interaction, presented by Colonel Walter L. Watson, Jr., Director of Operations, Maxwell AFB, November 7, 1994.
3. Vibratory Acceleration and Frequency on the Circulatory and Sensory Functions presented by Dr. Dianne L. McMullin, University of Nebraska-Lincoln, March 3, 1994.
4. Hybrid Architecture for Human-Machine Interface Design, presented by Dr. Nong Ye, Wright State University, Ohio, February 20, 1994.
5. The Application of Ergonomics to Design at Chrysler Corporation, presented by Dr. Deborah D. Thompson, Chrysler Corp., Auburn Hills, Michigan.
6. Investigating Blocking Phenomenon and Its Relations To the Occurrence of Errors, presented by Prof. Barbara Pioro, University of Wisconsin, Platteville.
7. Second Symposium on Human Interaction with Complex Systems, Four Seasons Holiday Inn, Greensboro, NC, (Dr. Celestine Ntuen, General Chair, Drs. E. H. Park and J. H. Kim, Program Chairmen).
8. Third Symposium on Human Interaction with Complex Systems, Holiday Inn, Fairborn, Ohio, Co-host with Wright-State University, Dayton, Ohio, (Dr. Celestine Ntuen, General Chair, Dr. O. Garcia, Program Chair).

C.1.3 Student Activities

During the grant period, nine graduate and four undergraduate students were supported. They met once a week to discuss research methods, academic preparation, and mentorship. The undergraduate students, advised by Ms. Pioro, presented six (6) poster papers at the National Conference on Undergraduate Research (NCURIX) held on April 19-22, 1995 in Schenectady, New York and presented six papers on cockpit design at the NAFEO 20th National Conference on Blacks in Higher Education held in Washington, DC from March 15-19, 1995. Under Ms. Pioro's supervision, the student chapter of the Human Factors and Ergonomics Society was organized. The students, as a part of their professional development, visited the Guilford Technical Community College Aviation Center, UNC-Chapel Hill Computer Science Department Virtual Reality Laboratory and Atlantic Aero Flight Training Center.

C.1.4. Impact of Research Program

One of the outstanding accomplishments in this project was organizing the **Human-Machine Systems Engineering (HMSE) Group** in Fall 1993 as a part of our pipeline recruitment process. This group consisted of students from three disciplines: Industrial Engineering, Computer Science and Electrical Engineering. The group meets weekly for discussions and seminars. It has been taking very active and positive roles in promoting students' interests in the area of HMSE and provides a necessary means to nurture them. This year's group has grown to 37 undergraduate students and 21 graduate students from the combined three departments. Some of the highlight activities follow.

1. The group meets every Wednesday for discussions and seminars. This keeps the members updated in HMSE knowledge. It also provides opportunities for students to make presentations of their research.
2. The group provides an excellent means of mentoring as follows.
   - The investigators have been mentoring 21 graduate students through the weekly meetings and research advisement.
   - The undergraduate students have been mentored by both the investigators and the graduate students. Each graduate student mentors an average of two undergraduate students.
   - Each undergraduate member provides counseling service to a freshman during pre-registration period.

- All undergraduate students are assigned team projects which are guided primarily by their graduate mentors.

3. The group promotes a strong interest in the field of HMSE among students and faculty, which keeps the newly established HMSE option moving strongly. The Industrial Engineering Department was invited to submit a proposal to create a Ph.D. program in Fall 1997. HMSE is one of the three main areas in the proposal.
4. This project successfully motivated nine African-American students to pursue their advanced degrees in Industrial Engineering at North Carolina A&T State University.
5. The group successfully hosted the 1994 and 1995 Symposia on Human Interaction with Complex Systems in Greensboro, North Carolina. Many outstanding scholars in this field, from a variety of different states and countries, attended. Twenty four panel members participated in four round table panel discussions and 30 technical presentations were made during each Symposium. The overall evaluations were outstanding. Our members and faculty had an opportunity to interact with some of the top-notch researchers in the field. Much was learned from the presentations.
6. The 1996 Symposium on Human Interaction with Complex Systems was held in Dayton, Ohio in August. This Symposium was co-sponsored with Wright State University. The HMSE Interest Group thought it time for the Symposium to be held outside of Greensboro so this field could be promoted more, and our HMSE program's visibility would be enhanced.
7. The group takes prominent roles in running a successful high school enrichment program called the Summer Minority Young Scholar Para-Research Program (PRP) in June and July for the past five years. The HMSE student members provide instruction and mentorship to the high school participants.
8. One of the group, Maranda McBride, received the NAMASKR Award, which is given to the outstanding senior in the College of Engineering. She was recruited to our graduate program for a Master's degree, and will study in the area of HMSE. She received and NSF Fellowship for her period of study.
9. Two graduate students, Tracy Bell and Dara Strickland, received NSF Fellowships to study in Japan during the summer of 1996. They had research opportunities at the Japan Space Institute in Tokyo in the area of HMSE.

C.1.4. New Course Developments

INEN 660 : Human Reliability and Performance in Control Task
INEN 664 : Safety Engineering
INEN 665 : Human-Machine Systems
INEN 740 : Human-Computer Interaction
INEN 789 : Advanced Topics in Human Factors

C.2. Travel

1. All investigators, Drs. C. Ntuen, J. Deeb and E. Park visited NASA-Langley Research Center to discuss our research direction and to collect research materials in May 1992.
2. Drs. C. Ntuen and J. Deeb attended a workshop in June 1992 on "Fundamentals of Flight Simulation" organized by MIT.
3. Drs. Ntuen and Deeb attended the 1993 International Conference for Industrial Engineers in May 1993 to present technical papers which were developed from this research's findings.
4. Dr. C. Ntuen presented a technical paper at the 15th International Conference on Computers and Industrial Engineering held in Cocoa Beach, Florida in March 1993.
5. Dr. J. Deeb presented a technical paper at the 2nd Industrial Engineering Research Conference held in Los Angeles, California in May 1993.

6. Two graduate students, W. Winchester and J. Chestnut, presented two technical papers at the 16th International Conference on Computers and Industrial Engineering held in Cocoa Beach, Florida in March 1994.
7. Dr. C. Ntuen presented a technical paper at the 45th Annual International Conference on Industrial Engineering held in Atlanta, Georgia in May 1994.
8. D. C. Ntuen visited the Flight Dynamic Division at the Wright Patterson Air Force Base in order to discuss research collaboration in Human Engineering in May 1994.
9. Drs. C. Ntuen, E. Park and J. Kim presented technical papers at the 1994 Symposium on Human Interaction with Complex Systems held in Greensboro, North Carolina in Sept. 1994.
10. Three undergraduate students of the NASA-CORE project, Lori President, Dara Strickland and Earl Brinson, presented two technical papers at the 1995 Annual Undergraduate Research Conference held in Schenectady, NY in April 1995.
11. A. Watson, graduate student, presented a technical paper at the 1995 Symposium on Human Interaction with Complex Systems held in Greensboro, North Carolina in September 1995.
12. Drs. C. Ntuen and E. Park attended the 46th Annual International Conference on Industrial Engineering held in Nashville, Tennessee in May 1995. Dr. C. Ntuen presented two papers.
13. Dr. C. Ntuen attended the 2nd Annual Conference on Advanced Distributed Simulation held in Washington, DC in September 1995.
14. All investigators, Drs. C. Ntuen, E. Park, J. Kim and B. Pioro, presented technical papers at the 1995 Symposium on Human Interaction with Complex Systems held in Greensboro, North Carolina in September 1995.
15. Dr. Linda Pierce and Dr. Mike Barnes from Army Research Laboratory were invited as panel members for the 1995 Symposium on Human Interaction with Complex Systems. As it can be shown from the attachment, this fulfilled the NASA-CORE's commitment for the Symposium as a sponsor.
16. Two graduate students, A. Watson and M. Pitman, presented a technical paper at the 16th International Conference on Computers and Industrial Engineering held in Miami, Florida in March 1996.
17. Four faculty investigators and seven graduate students attended the 1st NASA URC National Student Conference held in Greensboro, NC in February 1996.
18. Drs. C. Ntuen and E. Park presented three technical papers at the 1996 Symposium on Human Interaction with Complex Systems held in Dayton, Ohio in September 1996.

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Propulsion Group

PROPULSION RESEARCH

FINAL REPORT

Prepared for

Center for Aerospace Research
NASA Center of Research Excellence (NASA-CORE)
College Of Engineering
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by

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February, 1997

A. RESEARCH SUMMARY

The group began research studies in two broad areas - airframe engine integration and engine cycle analysis for High Speed Civil Transport (HSCT) and hypersonic vehicle configurations. As the research component was only in existance for the last two years of the grant (1995-96), projects were of a relatively short duration while the research focus and interests were established. Specifically, topics investigated were:

1. Three discipline coupling among structural response, flow field analysis, and propulsion performance involving identification of significant coupling variables and assessing influence of design variable changes and interdisciplinary influences.
2. Analytical model development: structure - flow - control - propulsion coupling beginning with closed form or numerical solutions combinations.
3. Classification of optimal solution methodology for three discipline problem with particular emphasis on the structure flow coupling using schema recently presented in the literature.
4. Student led study assessing the emissions requirements for the next generation supersonic transport construct.
5. Propulsion system cycle analysis from a second law entropy generation point of view, using exergy "bookeeping" for identifying cycle improvement areas.
6. Effect of engine box design on propulsive performance.
7. Genetic algorithm optimization of propulsion system performance.

Since the propulsion group is relatively new, a number of research topics were initially pursued. A mid-year review in 1995 offered guidance to consolidate the research efforts to a more defined focus. Specifically, work in the items below serves as a beginning and foundation for developing a unified multidisciplinary design and optimization methodology for aircraft systems. The other mentioned topics are interfaced with the structures, control and CFD groups, and will provide opportunities for enhancing intergroup interaction. A more clear definition of the group's activities were defined as:

1. Structure-Propulsion-Flow-Control Coupling: This involves the interfacing of individual modules in order to predict air flow properties which are consistent with aircraft deflections in response to the surrounding pressure field. Subsequently, we may predict the effect of such coupling on the propulsion system performance with respect to intake air capture rate and thermodynamic properties. Analytical models for approximating the coupled interaction will be explored. Such formulations will allow development of analysis methodologies which then can be applied to higher fidelity models utilizing computational modules (FEA, CFD, etc).
2. Sensitivity Analysis: Multidisciplinary Design/Optimization (MDO) procedures for analyzing the influences among coupled disciplines. This primarily involves the construction of a global sensitivity matrix which contains the partial derivatives of outputs with respect to design and coupling variables. Our main concern is the influence on operating parameters such as Mach number and altitude (dynamic pressure) on engine propulsion measures - efficiency, specific thrust, etc.
3. Cycle Analysis and Optimization: Performance analysis of engine system constructs: turbojet, ramjet, scramjet, and variable cycle for operating conditions consistent with HSCT and hypersonic vehicle mission envelopes. Includes optimal configuration studies and cycle optimization using techniques such as genetic algorithms and geometric programming.
4. Combustion Driven Flutter: application of developed flutter analysis (structures-CFD groups) to engine structural responses to combustion excitation.

In addition to efforts for analysis of propulsion system performance, a primary focus is the development of methodologies for integrating such systems with the entire system construct, ie., the airframe, required control stratagies, and mission requirements attainment. A major thrust is the application of multidisciplinary design and optimization (MDO) techniques to the overall system design problem.

The integration of disciplinary analyses and outputs which have been traditionally not related until the end of the design cycle, is accomplished by coupling them via generalized global sensitivity equations (GSE). The object is to compute a vector of total derivatives relating the sensitivity of one discipline's outputs to variations in global design variables and outputs from other disciplines; thus the interactions are quantitatively captured. Techniques such as analytical differentiation (when possible), finite differencing, and use of the Implicit Function Theorem accomplishes these calculations.

The resulting gradient information can be utilized in an optimization schema, either on the full models or upon some reduced order approximation. Care must be taken for selecting both the appropriate optimization routine, and also with the resulting accuracy of the reduced model if one is used. It is also necessary to select appropriate coupling variables, that is those parameters which are germane to two or more disciplines which link the disciplinary modules together.

Clearly, modeling efforts must be concerned with sufficiently representing the physics of both the individual disciplines and the mechanisms which govern the interrelated coupling. It is this notion which has focused the work to date, to acquire an understanding of the key features of propulsion systems which identify the resulting design influences upon and by other aspects of the aero vehicle design. These efforts continued into 1996.

More detail about the stated projects follows:

1. Development of a quasi-steady simulation model for an accelerating ramjet missile: This problem was selected because each disciplinary aspect can be adequately modelled with closed form or numerical solutions. These modules include:

    1. Taylor-Maccoll conic flow computation for estimating the shock affected flow field.
    2. An annular solid fuel combustion process with fuel regression rate calculation, and the subsequent propulsion performance.
    3. A simple cylindrical structural model with varying characteristics due to the fuel burn.
    4. An time integration for velocity determinations.
    5. A low order proportional control loop for stability analysis.

3. Ambient Air Perturbations Effects on Propulsive Performance: Integration of thermal response effects with controller design: A model to estimate the effects of air inlet variations on the heat transfer environment in a nacelle configuration. Time variations on thermal properties of inlet air can be represented in an amplitude/phase format which quickly lends to integration with a control loop.
4. Fluid structure interaction in propulsion components: Model development for coupling thermal and pressure fields with structural response of cylindrical shells. Potential applications to combustion driven flutter phenomena.
5. Super/hypersonic flow analysis: CFD analysis of reacting flows which characterize ram/scramjet engine environments.
6. MDO modeling computations: Identification of software tools which will facilitate mathematical operations of MDO analysis such as function approximations, numerical differentiation, optimization, etc.

B. RESEARCH PERSONNEL

Propulsion Coordinator: Dr. Mel Human, Associate Professor, Department of Mechanical Engineeering. The other rsearchers in the propulsion component are Dr. Kenneth Jones, Assistant Professor, Department of Mechanical Engineering and Dr. Ji-Yao Shen, Adjunct Associate Professor, in the College of Engineering.

C. STUDENT RESEARCH ACTIVITIES

Mr. Leslie King produced a master's thesis investigating the effect of HSCT engine box design on the vehicle's propulsion performance. Different engine configurations will entail a number of possible component arrangements and subsequent performance, and also a variety of air intake conditions due to surface interaction and shock wave positioning. For candidate arrangements, Mr. King evaluated the overall propulsive performance (overall efficiency, specific thrust) using empirical component performance correlations, and estimates of the air properties of the intake stream. This is being done over operating envelopes consistent with HSCT mission trajectories. The ultimate goal was the determination of various sensitivity coefficients with respect to the aircraft design.

Ms. Wanita Dunston, applied her summer experience of working at the Environmental Protection Agency (EPA) to address the emission requirements associated with the HSCT, contrasting such requirements with the old standards applied to the Concorde aircraft, and researching the technical approaches by which the new standards will be be met. This work was presented in a conference presentation Ms. Dunston's next assignment was to assist in the development of numerical tools for performing MDO mathematical operations, utilizing commercial mathematics packaged MACSYMA and TKSolver.

Ms. Pamela Groce, developed a FORTRAN routine which couples analytical solutions involving structural deformations and flow field pressure results. The primary goal is to evaluate an estimate of the convergence properties of an algorithm which iterates between structure and fluid modules. Later, such results will be applied to a program which uses finite element analysis in place of the analytical model.

Ms. Wanita Dunston, who completed her undergraduate requirements in December 1996, investigated the use of commercial software packages, for performing MDO mathematical operations. The work resulted in a cross referencing between the code's capabilities and the required mathematics for analyzing a full MDO problem. The next step of the problem which will suitable for an undergraduate project is to incorporate the steps in a program format. Ms. Dunston began graduate work this January, and will proceed with a thesis topic of modeling emmisions as a function of aircraft trajectory. This will be the input for a optimal control minimal emissions problem.

Ms. Natasha McRae has been working with Dr. Kenneth Jones using the CFD code GASP for analyzing reactive flows in hypersonic flow conditions. She is investigating the convergence characteristics of a nozzle flow, and the effect of adjusting control parameters such as relaxation tolerances.

MULTI-COMPONENT RESEARCH ACTIVITY

Interdisciplinary Research

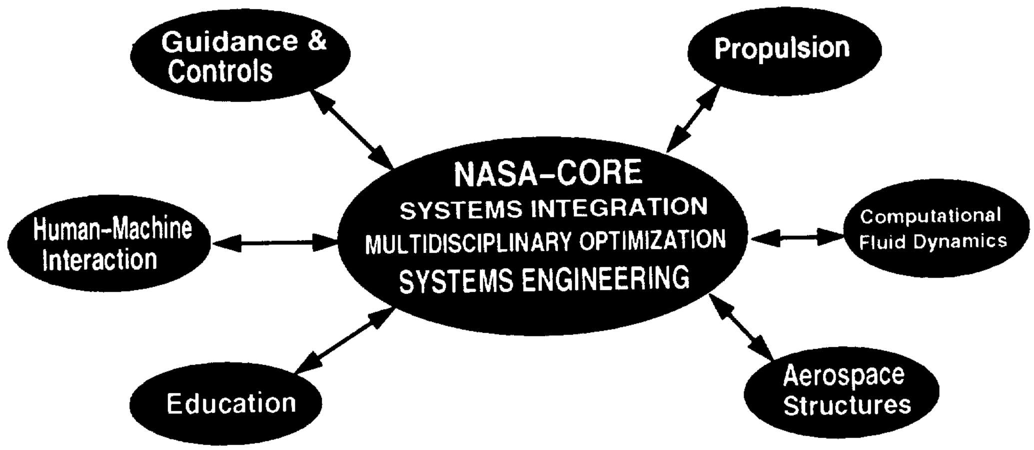
Interdisciplinary research, particularly when many disciplines and research tasks and interests are involved as is the case here, could be very complex. Figures 20-25 illustrate the program plan and the mechanics of the model. Figure 20 shows the basic multi-component interdisciplinary model, in which all the research components of NASA-CORE participate and contribute to achieve interdisciplinary analysis and multidisciplinary optimization (MDO). Interdisciplinary analysis and MDO are attained through system integration which utilizes results from each group through direct or peripheral (indirect) interaction. Figures 21 and 22 show representative cross-discipline tasks or research goals for each research component, with multiple tasks for some groups. Figure 22 contains the same information as Fig. 21 in 2-D matrix representation. In Fig. 22, the diagonal elements represent single-component tasks. For multidisciplinary design, Fig. 22 is three-dimensional, with the third dimension representing multiple systems and/or subsystems.

In Fig. 23, a point of contact (POC) is established in each research component and functional nodes or data throughput are identified to facilitate workflow either through direct (solid arrow) or peripheral (broken arrow) interaction. At the nodes, group goals are assessed and research results of the interdisciplinary tasks are optimized. At the center of Fig. 23, the data or group results are iterated for MDO and systems integration. Figure 24 illustrates the disciplinary functions and expected outcomes for an optimally designed high speed aircraft (model). To attain the goal of a robust systems engineering tool, Fig. 25 shows the process of the interdisciplinary research management for a single iteration optimization loop for "systems level" fidelity. Here, NASA's mission and the research activities of the NASA Field Centers are first structured as individual NASA-CORE goals to define our technical focus and objectives. Using the functional nodes to manage the group research leads to MDO model that yields effective system integration, the results of which are balanced against mission objectives and analysis, as well as goal evaluation, simulation and testing. Meeting set criteria and measures, this will then be translated into the systems design and implementation phase, as the output of the cycle. This output is then contrasted against NASA's mission to determine the optimal design.

2.1. Research Methodologies and Problem Definition

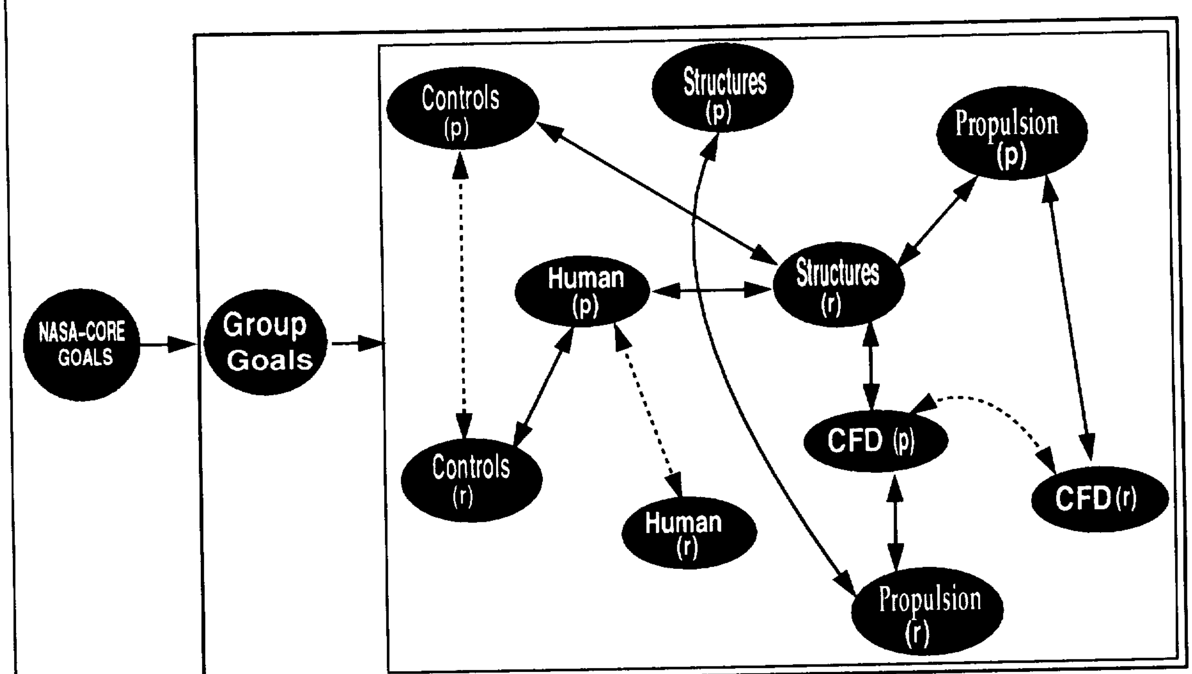
To implement the interdisciplinary model, we have adopted a three-step approach. The first step involves problem definition. Here, we identify an interdisciplinary problem and define component-level tasks and goals. This is shown in Figs. 21 and 22. In the second step, analyses of the component tasks are conducted to obtain results or appropriate task data. The results or data are then correlated and optimized at the functional nodes to determine parametric effects and/or sensitivity derivatives. In the third and final step, we will perform a single iteration systems integration and MDO, as shown in Fig. 23. The iteration is continued until an optimal design or solution is obtained. For a timely exchange of data and information, milestones for deliverables and outcomes for each component tasks are set. This three-step approach provides the framework to enable us achieve our interdisciplinary goals and objectives in a timely manner.

As a representative interdisciplinary research problem, we have chosen the analysis and design of the servo-elasto-aero-thermodynamics of high speed aircraft skin panels. This is a candidate multidisciplinary research problem in the development of high speed aircraft technologies and embraces nearly all the five research thrusts of NASA-CORE. The baseline tool for the interdisciplinary analysis is the NASA Ames multidisciplinary code, ENSAERO, which allows a three-component interdisciplinary research in CFD, Structures and Controls.



- DIRECT INTERACTION
- PERIPHERAL OR INDIRECT INTEGRATION
- SYSTEMS INTEGRATION
- MULTIDISCIPLINARY OPTIMIZATION
- DIRECT SUBSYSTEMS (CURRENT) ENGINEERING

Figure 20. Multi-Component Interdisciplinary Model



Direct Interaction

RESEARCH
COMPONENTS: CONTROL S AND GUIDANCE
HUMAN MACHINE INTERACTIONS
AEROSPACE STRUCTURES
COMPUTATIONAL FLUID DYNAMICS (CFD)
PROPULSION

p denotes Provider (Component)
r denotes Receiver (Component)

Figure 21. Cross-Disciplinary Tasks

Receiver (r) / Provider (p)	Structure	Control	CFD	Propulsion	Human–Machine
Structure	Structure	Panel vibration model	Panel modal deformation	MDO	
Control	Flutter control law	Control	Flutter control law	MDO	Model for rigid aircraft
CFD	Aerothermal loads on panel	Temperature distribution	CFD	Internal flow field characteristics	MDO
Propulsion	MDO		Propulsion system definition	Propulsion	MDO
Human–Machine		Data for pilot in–the–loop			Human–Machine

Figure 22. NASA-CORE interdisciplinary task matrix

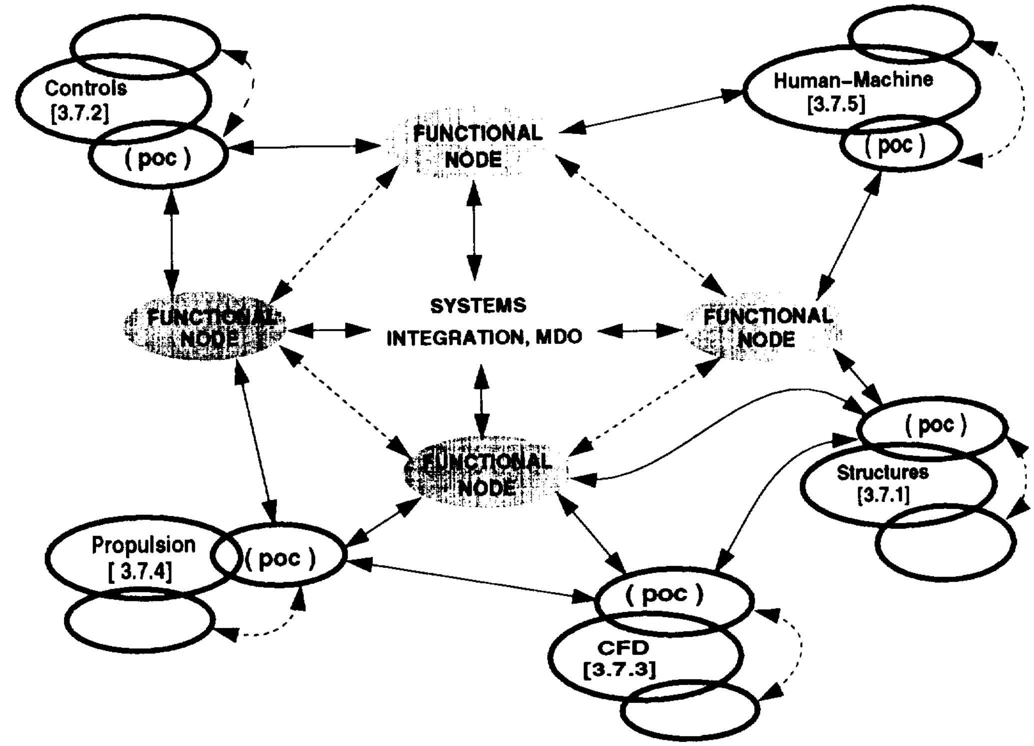


Figure 23. Interdisciplinary Functional Model

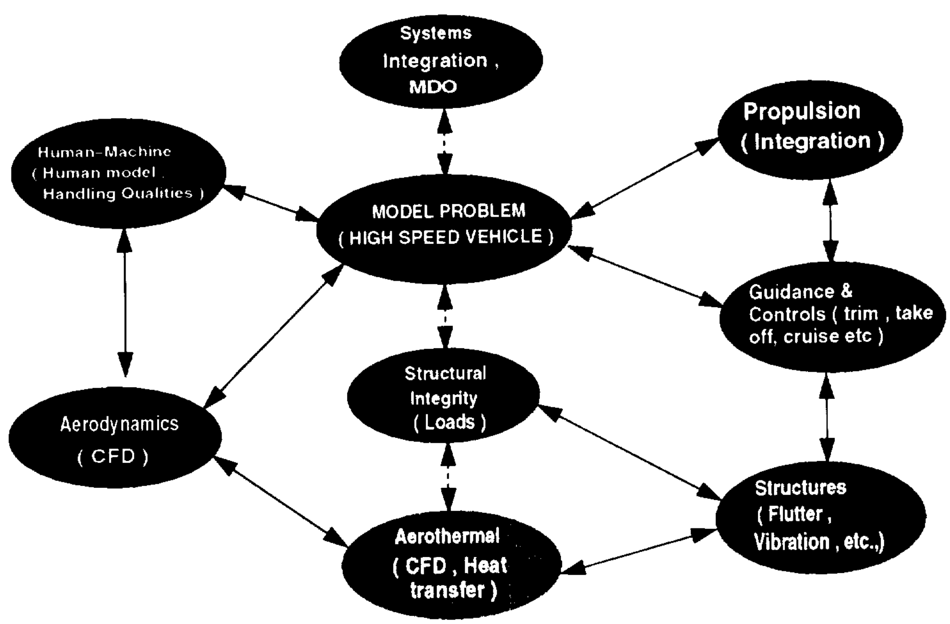


Figure 24. Interdisciplinary Functions and Modes

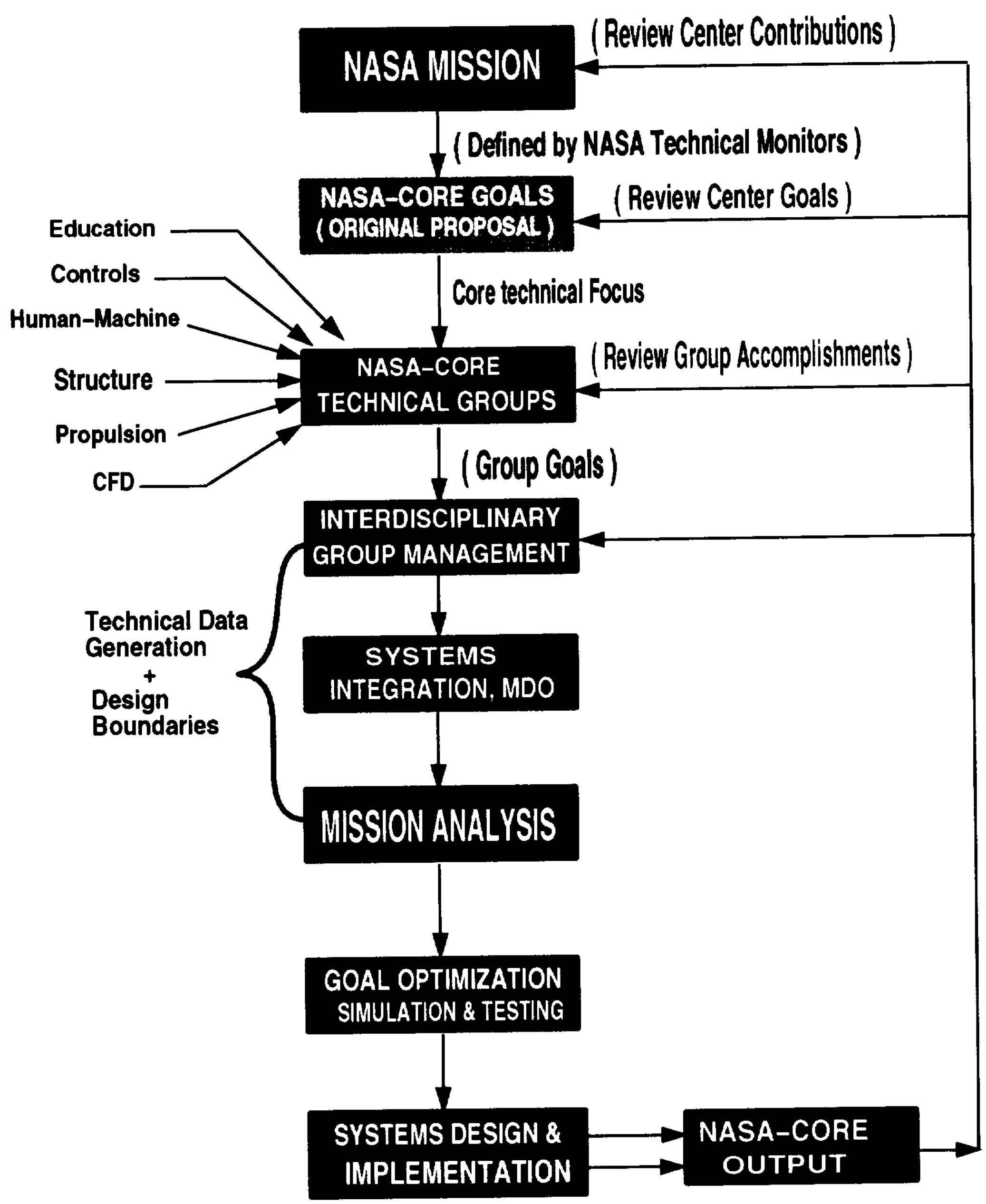


Figure 25. NASA-CORE Interdisciplinary Research Management

Appendix A

Undergraduate Student Handbook with Aerospace Option

Appendix B

Proceedings of the First National Student Conference of the NASA University Research Centers at Minority Institutions, March 31-April 2, 1996, Editors: E.O. Daso And S. Mebane.

Appendix C

Report of The Inaugural Meeting of the External Review Board Held October 10, 1996.

Appendix D

Course Descriptions

1. **MEEN 415. Aerodynamics** Credit 3(3-0)
The course begins with the fundamentals of fluid statics and dynamics followed by an introduction to inviscid flow theory with applications to incompressible flows over airfoils, wings, and flight vehicle configurations. Prerequisites: MATH 231 and MEEN 337
2. **MEEN 422. Aero Vehicle Structures I** Credit 3(3-0)
This course covers the determination of typical flight and landing loads and methods of analysis and design of aircraft structures to be able to withstand expected loads. Prerequisites: MEEN 336, MEEN 337 and MATH 331.
3. **MEEN 576. Propulsion** Credit 3(3-0)
This introductory course to aero propulsion systems includes coverage of one-dimensional internal flow of compressible fluids, normal shock, flow with friction, and simple heat addition. The basic concepts are applied to air-breathing aircraft propulsion systems. Prerequisites: MEEN 415 or 416, MEEN 441.
4. **MEEN 577. Aerodynamics and Propulsion Laboratory** Credit 1(0-2)
This is a laboratory course which provides experimental verification of concepts learned in MEEN 415 and MEEN 576. Experiments are performed that reinforce the concepts from the lecture courses including wind tunnel experiments and performance of a gas turbine engine. Prerequisite: MEEN 415. Corequisite: MEEN 576.
5. **MEEN 578. Flight Vehicle Performance** Credit 3(3-0)
This course provides an introduction to the performance analysis of aircraft. Aircraft performance in gliding, climbing, level, and turning flight are analyzed as well as calculation of vehicle take off and landing distance, range and endurance. Prerequisites: MATH 231 and MEEN 337.
6. **MEEN 580. Aerospace Vehicle Design** Credit 3(2-2)
This is the capstone design course for the Aerospace option. This course requires the synthesis of knowledge acquired in previous courses and the application of this knowledge to the design of a practical aerospace vehicle system. Prerequisites: MEEN 422, MEEN 474, MEEN 576, MEEN 578 and ELEN 410.
7. **MEEN 651. Aero Vehicle Structures II** Credit 3(3-0)
This course covers deflection of structures, indeterminate structures, fatigue analysis, and minimum weight design. Finite element methods and software are utilized. Prerequisite: MEEN 422.
8. **MEEN 652 Aero Vehicle Stability and Control** Credit 3(3-0)
This technical elective course covers longitudinal, directional and lateral static stability and control of aerospace vehicles. It also covers linearized dynamic analysis of the motion of a six degree-of-freedom flight vehicle in response to control inputs and disturbance through the use of the transfer function concept, plus control of static and dynamic behavior by vehicle design (stability derivatives) and/or flight control systems. Prerequisites: MEEN 415, MEEN 422 and ELEN 410.
9. **MEEN 653 Aero Vehicle Flight Dynamics** Credit 3(3-0)
This technical elective course covers the basic dynamics of aerospace flight vehicles including orbital mechanics, interplanetary and ballistic trajectories, powered flight maneuvers and spacecraft stabilization. Prerequisites: MATH 332, MEEN 337 and MEEN 422.
10. **MEEN 654 Advanced Propulsion** Credit 3(3-0)
This technical elective is a second course in propulsion. It covers the analysis and design of individual components and complete air-breathing propulsion systems including turbo fans, turbo jets, ram jets and chemical rockets. Prerequisite: MEEN 576.

11. **MEEN 655. Computational Fluid Dynamics** Credit 3(3-0)
This technical elective course provides an introduction to numerical methods for solving the exact equations of fluid dynamics. Finite difference methods are emphasized as applied to viscous and inviscid flows over bodies. Students are introduced to a modern computational fluid dynamics computer code. Prerequisites: MATH 332 and MEEN 415 or 416.

12. **MEEN 656. Boundary Layer Theory** Credit 3(3-0)
This course covers the fundamental laws governing flow of viscous fluids over solid boundaries. Exact and approximate solutions are studied for various cases of boundary layer flow including laminar, transitional and turbulent flow. Prerequisite: MEEN 415 or 416.

13. **ELEN 410. Linear Systems and Control** Credit 3(3-0)
Introduction to control theory. This includes: control system modeling and representation, features of feedback control systems, state space representation, time domain analysis, stability analysis, root locus, and design compensation. Prerequisite: ELEN 300 (ELEN 200 for ME Aerospace Option students).

Appendix E

NASA-CORE Educational Program Participants And Their Activities

1. Dr. William J. Craft, Chairperson, Department of Mechanical Engineering and Professor of Mechanical Engineering (Management and Curriculum Development and Graduate Student Supervision)[1]
2. Dr. David E. Klett, Undergraduate Coordinator and Professor of Mechanical Engineering (Curriculum Development, Equipment Purchasing, and Graduate Student Supervision)[1]
3. Dr. Endwell O. Daso, Adjunct Professor of Mechanical Engineering and NASA-CORE Director (Overall Management of the Center and Course Instruction)
4. Dr. Kenneth Jones, Assistant Professor of Mechanical Engineering (Teaching and Curriculum Development in Aerodynamics & Propulsion Courses & Laboratory)[2]
5. Dr. P. Frank Pai, Assistant Professor of Mechanical Engineering (Teaching and Research in Aero Structures)[3]
6. Dr. Suresh Chandra, Research Professor of Mechanical Engineering (Teaching and Research in CFD)[3]
7. Dr. A. Homaifar, Associate Professor of Electrical Engineering (Teaching Controls in the Electrical Engineering Department)[3]
8. Dr. Ed Shackelford, Adjunct Assistant Professor of Mechanical Engineering (Laboratory Development in Aerodynamics and Propulsion) [2]

Notes:

1. NASA-CORE funds formally were used by Drs. Craft and Klett on a release time basis.
2. Drs. Jones, Song, and Shackelford were supported to teach or to do laboratory development.
3. Drs. Pai, Chandra, and Homaifar taught courses required for students electing the new Aerospace Option curriculum without cost to NASA.

APPENDIX F

Laboratory Manual for Aerodynamics And Propulsion Laboratory

REPORT DOCUMENTATION PAGE

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The Center for Aerospace Research: NASA Center of Research Excellence (NASA-CORE) at North Carolina A&T State University is a multidisciplinary research center established by NASA in January 1992. The objectives of the Center are: to educate students in aerospace engineering, the conduct of aerospace research to establish a strong capability, and to enhance opportunities for socially- and economically-disadvantaged persons in aerospace engineering and technologies profession.

In education and training, we have established a quality program through curriculum and laboratory development to educate and train students in state-of-the-art aerospace research and provide opportunities for students to develop the background for research in NASA-related disciplines. An Aerospace Engineering Option has been establishment within the undergraduate mechanical engineering curriculum, and provides students the opportunity to take traditional aerospace engineering courses.

NASA-CORE conducts interdisciplinary research to advance the state-of-the-art in aerospace research. In this interdisciplinary framework, five components: Aerospace Structures, Controls and Guidance, Computational Fluid Dynamics, Human-Machine Interactions, and Propulsion conduct innovative research to develop systems engineering and design tools in support of NASA's mission in high speed aircraft and spacecraft technologies development. The Center's researchers have developed analytical and design tools for the design of next generation supersonic aircraft, hypersonic vehicles and spacecraft.

14. SUBJECT TERMS

Aerospace Research: Education, Aerospace Structures, Controls and Guidance, Computational Fluid Dynamics, Human-Machines Systems Engineering, Propulsion, Interdisciplinary Research

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